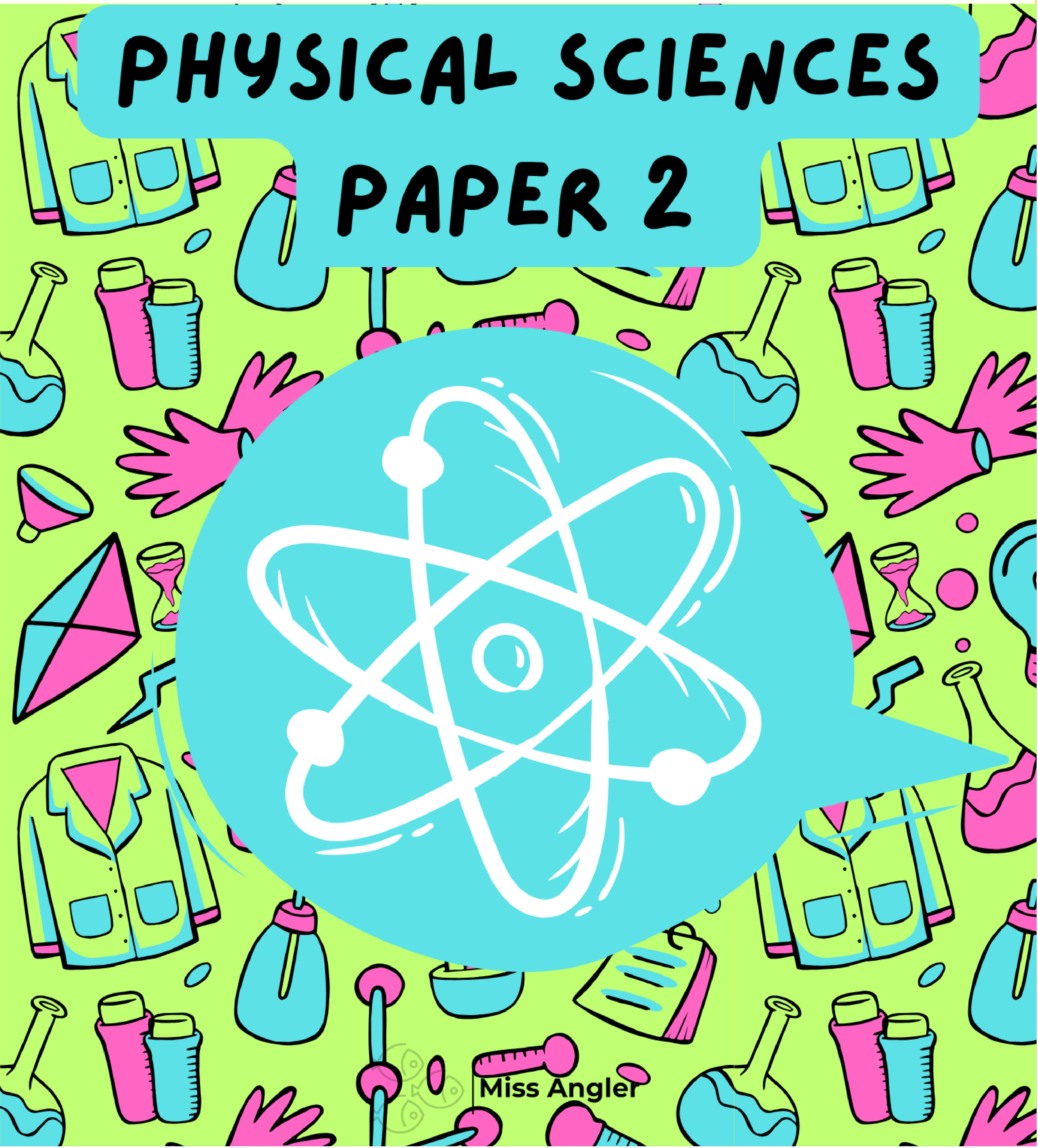
THE CHEAT SHEET

Grade
12
CAPS

PHYSICAL SCIENCES
PAPER 2



Miss Angler

THE CHEAT SHEET: GR. 12 PHYSICAL SCIENCES: PAPER 2

Miss Angler

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ACKNOWLEDGEMENTS
Department of Basic Education pg. 15 - 17, 67, 91, 97 & 98.

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HOW TO USE THIS STUDY GUIDE

PLEASE REMEMBER: This study guide does not replace your textbook or the instruction of your teacher. Its purpose is to make learning and revision EASY!

Difficulty levels of questions

Your exam will include questions covering three difficulty levels.
Each level of question will require a different level of understanding and way of answering the question.

The difficulty levels are summarized in this study guide using the acronym **C.A.P:**

C

COMPREHENSION AND RECALL QUESTIONS

These are common questions which include definitions and calculation questions that look similar to the questions covered in class. Approximately **55%** of Paper 2 (Chemistry) will include questions on this level.

A

ANALYSIS AND APPLICATION QUESTIONS

These are more complex questions which involves applying the knowledge and skills learned in this chapter. Approximately **35%** of Paper 2 (Chemistry) will include questions on this level.

P

PROBLEM- SOLVING QUESTIONS

These are questions that require critical thinking and being able to make connections between different representations of information and integrating different topics. They are not familiar questions, but are able to be solved through critical analysis. Approximately **10%** of Paper 2 (Cheimstry) will include questions on this level.

WORKED EXAMPLE KEY

This study guide will highlight which questions are classified under each difficulty level. Look out for **C, A or P** next to each question.

KEY NOTES

In this study guide, the worked examples have explanations added.

⚛ Note

💡 Scenario

🔗 Answer

Worked example
1.Multiple choice questions

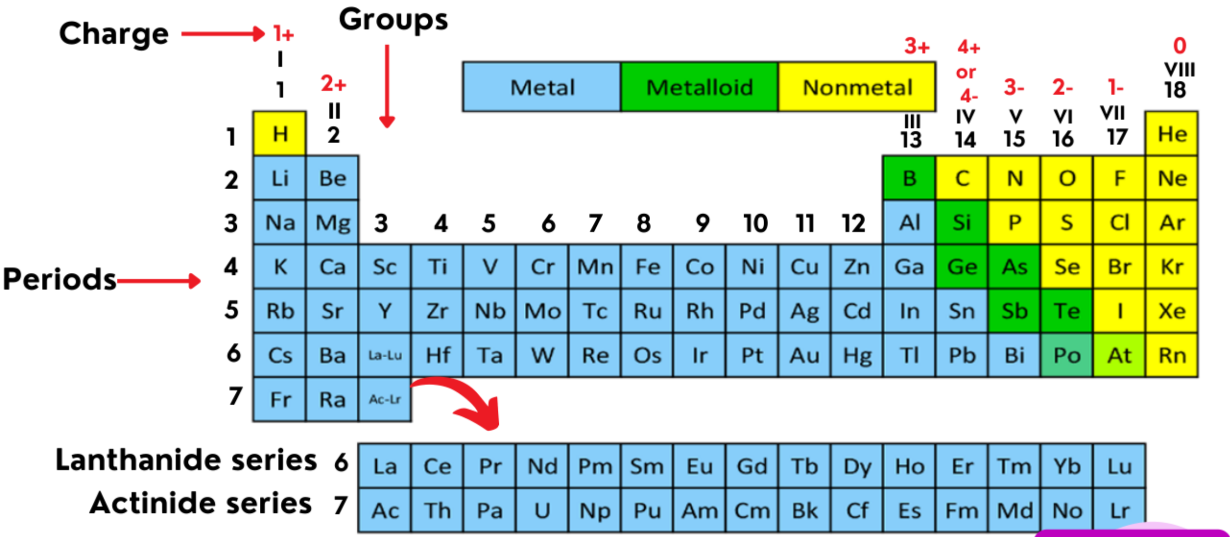
C + A

› Question

PAPER 2
TIPS FOR SUCCESS 100%

Periodic table of elements

- The periodic table of elements lists all the elements known to man, to date there are 118 elements on the periodic table.
- The periodic table is arranged in order of increasing atomic number or number of protons.
- Each vertical column is called a group and the elements in the same group have similar chemical properties. There are 18 groups on the periodic table.
- Each horizontal row is called a period. There are 7 periods on the periodic table.



Charge	1+	2+											3+	4+ or 4-	3-	2-	1-	0
	I	II											III	IV	V	VI	VII	VIII
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H																	He
2	Li	Be											B	C	N	O	F	Ne
3	Na	Mg											Al	Si	P	S	Cl	Ar
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba	La-Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra	Ac-Lr															

Lanthanide series 6	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Actinide series 7	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

PRO-TIPS

Always fill in the charges on the periodic table recieved.

Diatomic molecules

Certain elements exist as diatomic molecules on their own in nature, as they are more stable as diatomic molecules than single atoms.

List of diatomic molecules:

1. Hydrogen (H_2)
2. Nitrogen (N_2)
3. Oxygen (O_2)
4. Fluorine (F_2)
5. Chlorine (Cl_2)
6. Bromine (Br_2)
7. Iodine (I_2)

NOTE:
di = two. In diatomic molecules two of the same atoms bond in a covalent bond.

Naming compounds and writing chemical formula

Naming compounds containing monoatomic ions

When naming compounds containing a metal and a non- metal:

- The full name of the metal is always written first, followed by the name of non – metal.
- The name of the non - metal ends in the suffix **– ide.**

Example

NaBr is named as sodium bromide

Polyatomic ions

Charge 1-		**Charge 2-**		**Charge 3-**		**Charge 1+**	
OH^-	Hydrox**ide** ion	SO_4^{2-}	Sulph**ate ion**	PO_4^{3-}	Phosph**ate ion**	Ammonium **ion**	NH_4^+
NO_3^-	Nitr**ate ion**	SO_3^{2-}	Sulph**ite ion**			Hydronium **ion**	H_3O^+
NO_2^-	Nitr**ite ion**	CO_3^{2-}	Carbon**ate ion**				
ClO_3^-	Chlor**ate ion**	$Cr_2O_7^{2-}$	Dichrom**ate ion**				
MnO_4^-	Permangan**ate ion**	$(COO)_2^{2-}$ OR $C_2O_4^{2-}$	Oxal**ate ion**				
HCO_3^-	Bicarbonate ion/ hydrogen carbonate **ion**						
HSO_4^-	Hydrogen sulphate **ion**						
HSO_3^-	Hydrogen sulphite **ion**						
CH_3COO^-	Ethanoate ion/acetate **ion**						

PRO-TIPS

- Know the list of polyatomic ions:
- The name of the polyatomic ions, chemical formulae and charge.
- Polyatomic ions are commonly encountered in acids and bases and REDOX reactions.

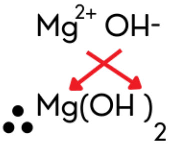
Writing chemical formulae

A chemical formula is a way of expressing the ratio in which the atoms bond in a compound, using chemical symbols and numbers.

When writing chemical formulae: In a neutral compound, the net (total) charge of the compound is equal to 0.

Method to do this: Apply the CROSSOVER RULE to write chemical formula. When applying the crossover, crossover the charges and omit the signs.

Example: Chemical formula for magnesium hydroxide.



PRO-TIPS

When writing chemical formulae containing polyatomic ions, if more than one of the same polyatomic ion bonds in the compound, brackets are placed around the polyatomic ion, and the subscript indicates how many of that polyatomic ion bonds in the compound.

NOTE:
In this example, in order to form a neutral compound, two hydroxide ions must bond to one magnesium ion

Elements with varying valencies and charges

Transition metals (and some other elements such as tin (Sn) and lead (Pb) have varying charges and varying valencies in nature. To indicate this, the valency of the element is indicated using roman numerals next to the name of the element.

Charge 1+		Charge 2+		Charge 3+		Charge 4+	
Ag^{+}	**Silver ion**	Cu^{2+}	Copper (II) ion	Fe^{3+}	Iron (III) ion	Mn^{4+}	Manganese (IV) ion
Cu^{+}	Copper (I) ion	Pb^{2+}	Lead (II) ion	Cr^{3+}	Chromium (III) ion	Pb^{4+}	Lead (IV) ion
		Zn^{2+}	**Zinc ion**	Co^{3+}	Cobalt (III) ion	Sn^{4+}	Tin (IV) ion
		Hg^{2+}	Mercury (II) ion	Hg^{3+}	Mercury (III) ion		
		Fe^{2+}	Iron (II) ion	Ni^{3+}	Nickel (III) ion		
		Sn^{2+}	Tin (II) ion				
		Cr^{2+}	Chromium (II) ion				
		Mn^{2+}	Manganese (II) ion				
		Co^{2+}	Cobalt(II) ion				
		Ni^{2+}	Nickel (II) ion				

PRO-TIPS

Silver and zinc occur more abundantly in nature with silver having a valency of 1 and zinc a valency of 2. Therefore it is **NOT necessary** to indicate the valency using roman numerals in brackets when naming these elements.

Balancing chemical reactions

- The substances on the left- hand side of the reaction equation are the reactants.
- The substances on the right - hand side of the reaction equation are the products.
- When balancing chemical reactions, the number of atoms on the left hand side must equal the number of atoms on the right hand side. Only the co - efficients i.e., the number of moles can be changed. Do not change the subscripts of the chemical formulae of the substances, as this changes the chemical composition of the substance.

✓ **Tip:**

- In most chemical equations: Get the **odd** number of atoms on either side of the reaction equation **to even.**
- When specified, indicate the states of matter of the reactants and products:
  Solids (s)
  Pure liquids (l)
  Gases (g)
  Aqueous solutions (aq)

NOTE: An aqueous solution (aq) is a solution in which water is the solvent.

Example: in the Haber (Bosch) process, nitrogen gas reacts with hydrogen gas to produce ammonia.

The balanced equation for the reaction is: $N_2 + 3H_2 \longrightarrow 2NH_3$

Scientific method

Variables in a scientific investigation:

- **Independent variable:** Variable that is **deliberately** changed or manipulated in an investigation. The independent variable does not depend on the dependent variable in the investigation.
- **Dependent variable:** Variable that is being **measured** in an investigation. The dependent variable depends on the independent variable in the investigation.
- **Control variable(s) or fixed variable(s):** Variable(s) that are kept constant in an investigation,to ensure that the investigation is a fair test.

Scientific terms used in a scientific investigation:

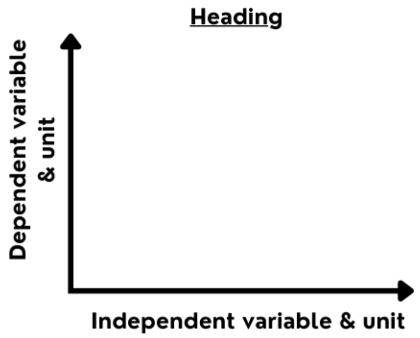
- **Investigative question**: Question about what is investigated. The investigative question must include:
  - The independent variable
  - The dependent variable
  - A question mark at the end

A mark will be lost for the investigative question if there is no question mark.

- **Hypothesis:** An educated guess; a **statement** of what the relationship between the independent and dependent variable is. The hypothesis is an answer to the investigative question.
- **Fair test:** An investigation is a fair test if it only has ONE independent i.e., one variable being deliberately changed or manipulated.

Graphs

Graph sketching

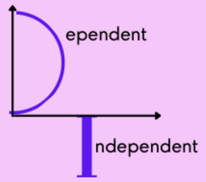


Tips for graph sketching:

- Sketch the graph and axes in pencil. The heading can be done in pen/pencil.
- The graph must be a reasonable size. A half a page can be used as a guideline.
- The graph must have a heading, which includes the **independent and dependent variable.** For example, concentration- time graph.
- <u>Underline</u> the heading.
- The axes must be labelled, with the **variables and units**. The independent variable is on the x - axis and the dependent variable on the y - axis.
- When sketching graphs, plotted values of x and y must be indicated on the **x - axis** and **y - axis**.

PRO-TIPS

Method to remember that the independent variable is on the x - axis and the dependent variable on the y- axis:



Graph interpretation

Straight - line graphs:

Gradient of the graph:

Gradient = $\frac{\Delta y}{\Delta x} = \frac{y_2 - y_1}{x_2 - x_1}$

Equation of the standard form of a straight - line graph: **$y = mx + c$**

Where:
m = gradient of the graph and/ or physical quantity represented by the gradient
c = y - intercept of the graph and/ or physical quantity represented by the y - intercept
x = input values and/ or physical quantity on the x - axis
y = output values and/ or physical quantity on the y - axis

PRO-TIPS

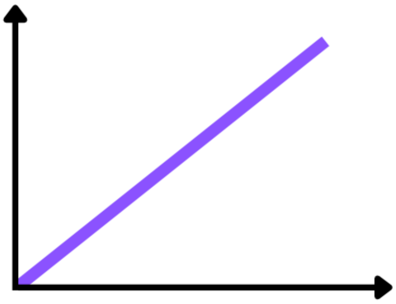
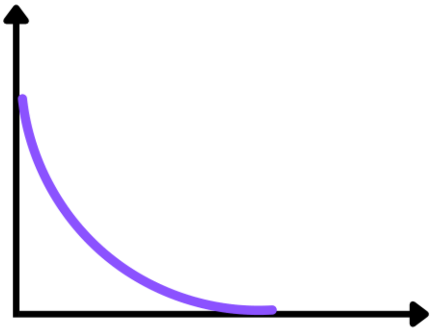
The variables in the straight - line graph equation can be replaced with physical quantities.

2D shape	Formula to calculate the area
Rectangle	A = l x b
Triangle	$A = \frac{1}{2} b \times \perp h$
Square	A = l x b **or** $A = s^2$ (where s = side)

Area under the graph:

As with the gradient of the graph, the **area under the graph** represents a different physical quantity, which can be calculated.

Relationship between variables: Graphical representation

Directly proportional relationship	**Inversely proportional relationship**
$a \propto b$ • As variable 'a' increases, variable 'b' increases by the same factor. • In a directly proportional relationship, the **ratio** between the two variables is constant	$a \propto \frac{1}{b}$ • As one variable 'b' increases, the other variable 'a' **decreases** by the same factor. • e.g., if variable 'b' is doubled, variable 'a' is halved. • In a inversely proportional relationship, the the **product** of two variables (e.g., a x b) is constant
 **NOTE:** A directly proportional relationship is represented by a straight - line graph which starts at the origin.	 **NOTE:** An inversely proportional relationship is represented by a smooth curve in quadrant I, since most real - life inversely proportionally relationships are positive.

General tips

- Format for **calculation questions**:

✓ Formula
✓ Substitution
✓ Answer + units.

To earn a formula mark, the substitution must be shown.

NOTE: Round off only the final answer to two decimal places.

- Use bullet points as far as possible when explaining answers.
- Learn the definitions as prescribed from the **Grade 12 guidelines.**
- Use the formulae given on the **data sheet.**

PAPER 2:CHEMISTRY SUMMARY OF THE GRADE 12 GUIDELINE DEFINITIONS

Organic Chemistry

- **Organic molecules:** molecules containing carbon atoms.
- **Molecular formula:** A chemical formula that indicates the type of atoms and the correct number of each in a molecule.
- **Structural formula:** A structural formula of a compound shows which atoms are attached to which within the molecule. Atoms are represented by their chemical symbols and lines are used to represent ALL the bonds that hold the atoms together.
- **Condensed structural formula:** This notation shows the way in which atoms are bonded together in the molecule, but DOES NOT SHOW ALL bond lines.
- **Hydrocarbon**: Organic compounds that consist of hydrogen and carbon only.
- **Homologous series**: A series of organic compounds that can be described by the same general formula OR in which one member differs from the next by a CH_2 group.
- **Saturated compounds:** Compounds in which there are no multiple bonds between C atoms in their hydrocarbon chains.
- **Unsaturated compounds:** Compounds with one or more multiple bonds between C atoms in their hydrocarbon chains.
- **Functional group:** A bond or an atom or a group of atoms that determine(s) the physical and chemical properties of a group of organic compounds.
- **Structural isomer:** Organic molecules with the same molecular formula, but different structural formulae.
- **Chain isomers:** Organic molecules with the same molecular formula, but different types of chains.
- **Positional isomers:** Organic molecules with same molecular formula, but different positions of the side chain, substituents or functional groups on the parent chain.
- **Functional isomers:** Organic molecules with the same molecular formula, but different functional groups.

Organic Chemistry (continued)

- **Vapour pressure:** The pressure exerted by a vapour at equilibrium with its liquid in a closed system.
- **Boiling point:** The temperature at which the vapour pressure of a susbtstance equals the (external) atmospheric pressure.
- **Melting point:** The temperature at which the solid and liquid phases of a substance are at equilibrium.
- **Cracking of alkanes:** The chemical process in which longer chain hydrocarbon molecules are broken down to shorter more useful molecules.

Rate and extent of reaction

- **Heat of reaction (ΔH):** The energy absorbed or released in a chemical reaction.
- **Exothermic reactions:** Reactions that release energy.
- **Endothermic reactions:** Reactions that absorb energy.
- **Activation energy:** The minimum energy needed for a reaction to take place.
- **Activated complex:** The unstable transition state from reactants to products.
- **Reaction rate:** The change in concentration of reactants or products per unit time OR change in the amount/mass/number of moles/volume of reactants or products per unit time.
- **Catalyst:** A substance that increases the rate of a chemical reaction without itself undergoing a permanent change.
- **Collision theory:** The collision theory is a model that explains reaction rate as the result of particles colliding with a certain minimum energy to form products.

Chemical equilibrium

- **Open system:** An open system is a system that continuously interacts with its environment.
- **Closed system:** A closed system is a system that is isolated from its surroundings.
- **Reversible reaction:** A reaction where products can be converted back to reactants.
- **Chemical equilibrium:** chemical equilibrium is a dynamic equilibrium when the rate of the forward reaction equals the rate of the reverse reaction.
- **Le Chatelier's Principle:** When the equilibrium in a closed system is disturbed, the system will re-instate a new equilibrium by favouring the reaction that will oppose the disturbance.

Acids and bases

- Define acids and bases according to Arrhenius theory:
  - **Acid:** Acids produce hydrogen ions (H^+) or hydronium ions (H_3O^+) in an aqueous solution.
  - **Base:** Bases produce hydroxide ions (OH^-) in an aqueous solution.

- Define acids and bases according Lowry-Brønsted theory:
  - **Acid:** An acid is a proton (H^+ion) donor.
  - **Base:** A base is a proton (H^+ ion) acceptor.

- **Strong acids:** Ionise completely in water to form a high concentration of H_3O^+ions. Examples of strong acids are: hydrochloric acid, sulphuric acid and nitric acid.

- **Weak acids:** Ionise incompletely in water to form a low concentration of H_3O^+ ions. Examples of weak acids are: ethanoic acid and oxalic acid.

- **Strong bases:** Dissociate completely in water to form a high concentration of OH^- ions. Examples of strong bases are: sodium hydroxide and potassium hydroxide.

- **Weak bases**: Dissociate incompletely in water to form a low concentration of OH^- ions. Examples of weak bases are: ammonia, calcium carbonate, potassium carbonate and sodium hydrogen carbonate.

- **Concentrated acids/bases:** Contain a large amount (number of moles) of acid/base in proportion to the volume of water.

- **Dilute acids/bases:** Contain a small amount (number of moles) of acid/base in proportion to the volume of water.

- **Hydrolysis**: The reaction of a salt with water.

- **Equivalence point of a titration:** The point at which the acid /base has completely reacted with the base/acid.

- **Endpoint of a titration:** The point where the indicator changes colour.

- **pH scale:** A scale of numbers from 0 to 14 used to express the acidity or alkalinity of a solution.

Electrochemistry

- **Galvanic cell:** A cell in which chemical energy is converted into electrical energy.

- **Electrolytic cell:** A cell in which electrical energy is converted into chemical energy.

- Define oxidation and reduction in terms of electron (e^-) transfer:
  Oxidation: is a loss of electrons.
  Reduction: is a gain of electrons.

- Define oxidation and reduction in terms of oxidation numbers:
  - **Oxidation:** An increase in oxidation number.
  - **Reduction:** A decrease in oxidation number.

- Define an oxidising agent and a reducing agent in terms of oxidation and reduction:
  - **Oxidising agent:** A substance that is reduced/gains electrons.
  - **Reducing agent:** A substance that is oxidised/loses electrons.

- Define an anode and a cathode in terms of oxidation and reduction:
  - **Anode:** The electrode where oxidation takes place.
  - **Cathode:** The electrode where reduction takes place.

- **Electrolyte:** A substance of which the aqueous solution contains ions OR a substance that dissolves in water to give a solution that conducts electricity.

- **Electrolysis**: The chemical process in which electrical energy is converted to chemical energy OR the use of electrical energy to produce a chemical change.

NOTE:

- Definitions are usually awarded **2 marks.**
- A definition is asked per question or per section of work
- All definitions must be stated as per the grade 12 guideline definitions.

PAPER 2 DATA SHEET

DATA FOR PHYSICAL SCIENCES GRADE 12
PAPER 2 (CHEMISTRY)

GEGEWENS VIR FISIESE WETENSKAPPE GRAAD 12
VRAESTEL 2 (CHEMIE)

TABLE 1: PHYSICAL CONSTANTS/*TABEL 1: FISIESE KONSTANTES*

NAME/*NAAM*	**SYMBOL/*SIMBOOL***	**VALUE/*WAARDE***
Standard pressure *Standaarddruk*	p^{θ}	$1,013 \times 10^5$ Pa
Molar gas volume at STP *Molêre gasvolume by STD*	V_m	$22,4\ dm^3 \cdot mol^{-1}$
Standard temperature *Standaardtemperatuur*	T^{θ}	273 K
Charge on electron *Lading op elektron*	e	$-1,6 \times 10^{-19}$ C
Avogadro's constant *Avogadro-konstante*	N_A	$6,02 \times 10^{23}\ mol^{-1}$

TABLE 2: FORMULAE/*TABEL 2: FORMULES*

$n = \frac{m}{M}$	$n = \frac{N}{N_A}$
$c = \frac{n}{V}$ or/*of* $c = \frac{m}{MV}$	$n = \frac{V}{V_m}$
$\frac{c_a V_a}{c_b V_b} = \frac{n_a}{n_b}$	pH = $-\log[H_3O^+]$
$K_w = [H_3O^+][OH^-] = 1 \times 10^{-14}$ at/*by* 298 K	
$E^{\theta}_{cell} = E^{\theta}_{cathode} - E^{\theta}_{anode} / E^{\theta}_{sel} = E^{\theta}_{katode} - E^{\theta}_{anode}$ or/*of* $E^{\theta}_{cell} = E^{\theta}_{reduction} - E^{\theta}_{oxidation} / E^{\theta}_{sel} = E^{\theta}_{reduksie} - E^{\theta}_{oksidasie}$ or/*of* $E^{\theta}_{cell} = E^{\theta}_{oxidisingagent} - E^{\theta}_{reducingagent} / E^{\theta}_{sel} = E^{\theta}_{oksideermiddel} - E^{\theta}_{reduseermiddel}$	
$q = I\Delta t$ $n = \frac{Q}{e}$ or/*of* $n = \frac{Q}{q_e}$	

TABLE 3: THE PERIODIC TABLE OF ELEMENTS
TABEL 3: DIE PERIODIEKE TABEL VAN ELEMENTE

KEY/*SLEUTEL*

Atomic number
Atoomgetal

Electronegativity
Elektronegatiwiteit

29
1,9 **Cu**
63,5

Symbol
Simbool

Approximate relative atomic mass
Benaderde relatiewe atoommassa

1 (I)	2 (II)	3	4	5	6	7	8	9	10	11	12	13 (III)	14 (IV)	15 (V)	16 (VI)	17 (VII)	18 (VIII)
1 2,1 **H** 1																	2 **He** 4
3 1,0 **Li** 7	4 1,5 **Be** 9											5 2,0 **B** 11	6 2,5 **C** 12	7 3,0 **N** 14	8 3,5 **O** 16	9 4,0 **F** 19	10 **Ne** 20
11 0,9 **Na** 23	12 1,2 **Mg** 24											13 1,5 **Aℓ** 27	14 1,8 **Si** 28	15 2,1 **P** 31	16 2,5 **S** 32	17 3,0 **Cℓ** 35,5	18 **Ar** 40
19 0,8 **K** 39	20 1,0 **Ca** 40	21 1,3 **Sc** 45	22 1,5 **Ti** 48	23 1,6 **V** 51	24 1,6 **Cr** 52	25 1,5 **Mn** 55	26 1,8 **Fe** 56	27 1,8 **Co** 59	28 1,8 **Ni** 59	29 1,9 **Cu** 63,5	30 1,6 **Zn** 65	31 1,6 **Ga** 70	32 1,8 **Ge** 73	33 2,0 **As** 75	34 2,4 **Se** 79	35 2,8 **Br** 80	36 **Kr** 84
37 0,8 **Rb** 86	38 1,0 **Sr** 88	39 1,2 **Y** 89	40 1,4 **Zr** 91	41 **Nb** 92	42 1,8 **Mo** 96	43 1,9 **Tc**	44 2,2 **Ru** 101	45 2,2 **Rh** 103	46 2,2 **Pd** 106	47 1,9 **Ag** 108	48 1,7 **Cd** 112	49 1,7 **In** 115	50 1,8 **Sn** 119	51 1,9 **Sb** 122	52 2,1 **Te** 128	53 2,5 **I** 127	54 **Xe** 131
55 0,7 **Cs** 133	56 0,9 **Ba** 137	57 **La** 139	72 1,6 **Hf** 179	73 **Ta** 181	74 **W** 184	75 **Re** 186	76 **Os** 190	77 **Ir** 192	78 **Pt** 195	79 **Au** 197	80 **Hg** 201	81 1,8 **Tℓ** 204	82 1,8 **Pb** 207	83 1,9 **Bi** 209	84 2,0 **Po**	85 2,5 **At**	86 **Rn**
87 0,7 **Fr**	88 0,9 **Ra** 226	89 **Ac**															
				58 **Ce** 140	59 **Pr** 141	60 **Nd** 144	61 **Pm**	62 **Sm** 150	63 **Eu** 152	64 **Gd** 157	65 **Tb** 159	66 **Dy** 163	67 **Ho** 165	68 **Er** 167	69 **Tm** 169	70 **Yb** 173	71 **Lu** 175
				90 **Th** 232	91 **Pa**	92 **U** 238	93 **Np**	94 **Pu**	95 **Am**	96 **Cm**	97 **Bk**	98 **Cf**	99 **Es**	100 **Fm**	101 **Md**	102 **No**	103 **Lr**

TABLE 4A: STANDARD REDUCTION POTENTIALS
TABEL 4A: STANDAARD-REDUKSIEPOTENSIALE

Increasing strength of oxidising agents/*Toenemende sterkte van oksideermiddels*

Half-reactions/*Halfreaksies*			**E^{θ} (V)**
$F_2(g) + 2e^-$	$\rightleftharpoons$	$2F^-$	+ 2,87
$Co^{3+} + e^-$	$\rightleftharpoons$	Co^{2+}	+ 1,81
$H_2O_2 + 2H^+ + 2e^-$	$\rightleftharpoons$	$2H_2O$	+1,77
$MnO_4^- + 8H^+ + 5e^-$	$\rightleftharpoons$	$Mn^{2+} + 4H_2O$	+ 1,51
$C\ell_2(g) + 2e^-$	$\rightleftharpoons$	$2C\ell^-$	+ 1,36
$Cr_2O_7^{2-} + 14H^+ + 6e^-$	$\rightleftharpoons$	$2Cr^{3+} + 7H_2O$	+ 1,33
$O_2(g) + 4H^+ + 4e^-$	$\rightleftharpoons$	$2H_2O$	+ 1,23
$MnO_2 + 4H^+ + 2e^-$	$\rightleftharpoons$	$Mn^{2+} + 2H_2O$	+ 1,23
$Pt^{2+} + 2e^-$	$\rightleftharpoons$	Pt	+ 1,20
$Br_2(\ell) + 2e^-$	$\rightleftharpoons$	$2Br^-$	+ 1,07
$NO_3^- + 4H^+ + 3e^-$	$\rightleftharpoons$	$NO(g) + 2H_2O$	+ 0,96
$Hg^{2+} + 2e^-$	$\rightleftharpoons$	$Hg(\ell)$	+ 0,85
$Ag^+ + e^-$	$\rightleftharpoons$	Ag	+ 0,80
$NO_3^- + 2H^+ + e^-$	$\rightleftharpoons$	$NO_2(g) + H_2O$	+ 0,80
$Fe^{3+} + e^-$	$\rightleftharpoons$	Fe^{2+}	+ 0,77
$O_2(g) + 2H^+ + 2e^-$	$\rightleftharpoons$	H_2O_2	+ 0,68
$I_2 + 2e^-$	$\rightleftharpoons$	$2I^-$	+ 0,54
$Cu^+ + e^-$	$\rightleftharpoons$	Cu	+ 0,52
$SO_2 + 4H^+ + 4e^-$	$\rightleftharpoons$	$S + 2H_2O$	+ 0,45
$2H_2O + O_2 + 4e^-$	$\rightleftharpoons$	$4OH^-$	+ 0,40
$Cu^{2+} + 2e^-$	$\rightleftharpoons$	Cu	+ 0,34
$SO_4^{2-} + 4H^+ + 2e^-$	$\rightleftharpoons$	$SO_2(g) + 2H_2O$	+ 0,17
$Cu^{2+} + e^-$	$\rightleftharpoons$	Cu^+	+ 0,16
$Sn^{4+} + 2e^-$	$\rightleftharpoons$	Sn^{2+}	+ 0,15
$S + 2H^+ + 2e^-$	$\rightleftharpoons$	$H_2S(g)$	+ 0,14
$2H^+ + 2e^-$	**$\rightleftharpoons$**	**$H_2(g)$**	**0,00**
$Fe^{3+} + 3e^-$	$\rightleftharpoons$	Fe	– 0,06
$Pb^{2+} + 2e^-$	$\rightleftharpoons$	Pb	– 0,13
$Sn^{2+} + 2e^-$	$\rightleftharpoons$	Sn	– 0,14
$Ni^{2+} + 2e^-$	$\rightleftharpoons$	Ni	– 0,27
$Co^{2+} + 2e^-$	$\rightleftharpoons$	Co	– 0,28
$Cd^{2+} + 2e^-$	$\rightleftharpoons$	Cd	– 0,40
$Cr^{3+} + e^-$	$\rightleftharpoons$	Cr^{2+}	– 0,41
$Fe^{2+} + 2e^-$	$\rightleftharpoons$	Fe	– 0,44
$Cr^{3+} + 3e^-$	$\rightleftharpoons$	Cr	– 0,74
$Zn^{2+} + 2e^-$	$\rightleftharpoons$	Zn	– 0,76
$2H_2O + 2e^-$	$\rightleftharpoons$	$H_2(g) + 2OH^-$	– 0,83
$Cr^{2+} + 2e^-$	$\rightleftharpoons$	Cr	– 0,91
$Mn^{2+} + 2e^-$	$\rightleftharpoons$	Mn	– 1,18
$A\ell^{3+} + 3e^-$	$\rightleftharpoons$	$A\ell$	– 1,66
$Mg^{2+} + 2e^-$	$\rightleftharpoons$	Mg	– 2,36
$Na^+ + e^-$	$\rightleftharpoons$	Na	– 2,71
$Ca^{2+} + 2e^-$	$\rightleftharpoons$	Ca	– 2,87
$Sr^{2+} + 2e^-$	$\rightleftharpoons$	Sr	– 2,89
$Ba^{2+} + 2e^-$	$\rightleftharpoons$	Ba	– 2,90
$Cs^+ + e^-$	$\rightleftharpoons$	Cs	- 2,92
$K^+ + e^-$	$\rightleftharpoons$	K	– 2,93
$Li^+ + e^-$	$\rightleftharpoons$	Li	– 3,05

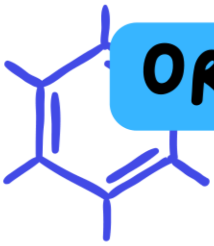
Increasing strength of reducing agents/*Toenemende sterkte van reduseermiddels*

TABLE 4B: STANDARD REDUCTION POTENTIALS
TABEL 4B: STANDAARD-REDUKSIEPOTENSIALE

Increasing strength of oxidising agents/*Toenemende sterkte van oksideermiddels* ↓

Half-reactions/*Halfreaksies*			**E^θ (V)**
$Li^+ + e^-$	$\rightleftharpoons$	Li	– 3,05
$K^+ + e^-$	$\rightleftharpoons$	K	– 2,93
$Cs^+ + e^-$	$\rightleftharpoons$	Cs	– 2,92
$Ba^{2+} + 2e^-$	$\rightleftharpoons$	Ba	– 2,90
$Sr^{2+} + 2e^-$	$\rightleftharpoons$	Sr	– 2,89
$Ca^{2+} + 2e^-$	$\rightleftharpoons$	Ca	– 2,87
$Na^+ + e^-$	$\rightleftharpoons$	Na	– 2,71
$Mg^{2+} + 2e^-$	$\rightleftharpoons$	Mg	– 2,36
$A\ell^{3+} + 3e^-$	$\rightleftharpoons$	$A\ell$	– 1,66
$Mn^{2+} + 2e^-$	$\rightleftharpoons$	Mn	– 1,18
$Cr^{2+} + 2e^-$	$\rightleftharpoons$	Cr	– 0,91
$2H_2O + 2e^-$	$\rightleftharpoons$	$H_2(g) + 2OH^-$	– 0,83
$Zn^{2+} + 2e^-$	$\rightleftharpoons$	Zn	– 0,76
$Cr^{3+} + 3e^-$	$\rightleftharpoons$	Cr	– 0,74
$Fe^{2+} + 2e^-$	$\rightleftharpoons$	Fe	– 0,44
$Cr^{3+} + e^-$	$\rightleftharpoons$	Cr^{2+}	– 0,41
$Cd^{2+} + 2e^-$	$\rightleftharpoons$	Cd	– 0,40
$Co^{2+} + 2e^-$	$\rightleftharpoons$	Co	– 0,28
$Ni^{2+} + 2e^-$	$\rightleftharpoons$	Ni	– 0,27
$Sn^{2+} + 2e^-$	$\rightleftharpoons$	Sn	– 0,14
$Pb^{2+} + 2e^-$	$\rightleftharpoons$	Pb	– 0,13
$Fe^{3+} + 3e^-$	$\rightleftharpoons$	Fe	– 0,06
$2H^+ + 2e^-$	**$\rightleftharpoons$**	**$H_2(g)$**	**0,00**
$S + 2H^+ + 2e^-$	$\rightleftharpoons$	$H_2S(g)$	+ 0,14
$Sn^{4+} + 2e^-$	$\rightleftharpoons$	Sn^{2+}	+ 0,15
$Cu^{2+} + e^-$	$\rightleftharpoons$	Cu^+	+ 0,16
$SO_4^{2-} + 4H^+ + 2e^-$	$\rightleftharpoons$	$SO_2(g) + 2H_2O$	+ 0,17
$Cu^{2+} + 2e^-$	$\rightleftharpoons$	Cu	+ 0,34
$2H_2O + O_2 + 4e^-$	$\rightleftharpoons$	$4OH^-$	+ 0,40
$SO_2 + 4H^+ + 4e^-$	$\rightleftharpoons$	$S + 2H_2O$	+ 0,45
$Cu^+ + e^-$	$\rightleftharpoons$	Cu	+ 0,52
$I_2 + 2e^-$	$\rightleftharpoons$	$2I^-$	+ 0,54
$O_2(g) + 2H^+ + 2e^-$	$\rightleftharpoons$	H_2O_2	+ 0,68
$Fe^{3+} + e^-$	$\rightleftharpoons$	Fe^{2+}	+ 0,77
$NO_3^- + 2H^+ + e^-$	$\rightleftharpoons$	$NO_2(g) + H_2O$	+ 0,80
$Ag^+ + e^-$	$\rightleftharpoons$	Ag	+ 0,80
$Hg^{2+} + 2e^-$	$\rightleftharpoons$	$Hg(\ell)$	+ 0,85
$NO_3^- + 4H^+ + 3e^-$	$\rightleftharpoons$	$NO(g) + 2H_2O$	+ 0,96
$Br_2(\ell) + 2e^-$	$\rightleftharpoons$	$2Br^-$	+ 1,07
$Pt^{2+} + 2e^-$	$\rightleftharpoons$	Pt	+ 1,20
$MnO_2 + 4H^+ + 2e^-$	$\rightleftharpoons$	$Mn^{2+} + 2H_2O$	+ 1,23
$O_2(g) + 4H^+ + 4e^-$	$\rightleftharpoons$	$2H_2O$	+ 1,23
$Cr_2O_7^{2-} + 14H^+ + 6e^-$	$\rightleftharpoons$	$2Cr^{3+} + 7H_2O$	+ 1,33
$C\ell_2(g) + 2e^-$	$\rightleftharpoons$	$2C\ell^-$	+ 1,36
$MnO_4^- + 8H^+ + 5e^-$	$\rightleftharpoons$	$Mn^{2+} + 4H_2O$	+ 1,51
$H_2O_2 + 2H^+ + 2e^-$	$\rightleftharpoons$	$2H_2O$	+1,77
$Co^{3+} + e^-$	$\rightleftharpoons$	Co^{2+}	+ 1,81
$F_2(g) + 2e^-$	$\rightleftharpoons$	$2F^-$	+ 2,87

Increasing strength of reducing agents/*Toenemende sterkte van reduseermiddels* ↑



ORGANIC CHEMISTRY: PART 1
NOMENCLATURE

What is organic chemistry?

Organic chemistry is the study of compounds containing the element carbon (C). Many organic compounds contain carbon and hydrogen, but they may also include any number of other elements (e.g., oxygen, halogens, nitrogen, phosphorus, silicon and sulphur).

All living things, including cells, enzymes and plants are organic, carbon containing compounds.

Definition: Organic molecules: Molecules containing carbon atoms.

General naming of organic molecules

Number of carbon atoms	Prefix
1	meth -
2	eth -
3	prop-
4	but-
5	pent-
6	hex-
7	hept-
8	oct-

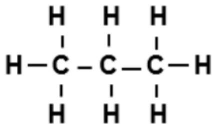
NOTE:
Organic chemistry does not include the study of CO_2 (carbon dioxide), CO (carbon monoxide) and compounds containing carbonates (CO_3^{2-}), bicarbonates (HCO_3^-), cyanides (CN^-), diamond, graphite.

Organic chemistry: Types of formulae

1. **Molecular formula:** A chemical formula that indicates the type of atoms and the correct number of each in a molecule. e.g., C_3H_8

2. **Structural formula:** A structural formula of a compound shows which atoms are attached to which within the molecule. Atoms are represented by their chemical symbols and lines are used to represent ALL the bonds that hold the atoms together.

e.g.



$$\begin{array}{ccccccc} & & H & & H & & H & & \\ & & | & & | & & | & & \\ H & - & C & - & C & - & C & - & H \\ & & | & & | & & | & & \\ & & H & & H & & H & & \end{array}$$

3. **Condensed structural formula:** This notation shows the way in which atoms are bonded together in the molecule, but DOES NOT SHOW ALL bond lines. e.g. $CH_3CH_2CH_3$

Organic chemistry - nomenclature: Definitions

In Organic chemistry, there are various **types** of organic molecules, and therefore different **homologous series** to which the organic molecules belong. The homologous series can be seen as the 'organic molecule family' to which the organic molecules belong. Organic molecules in the same homologous series have similar physical and chemical properties.

Definition: Homologous series: A series of organic compounds that can be described by the same general formula OR in which one member differs from the next with a CH_2 group.

The following **homologous series** (organic molecules) will be studied in this module:

1) Alkanes
2) Alkenes
3) Alkynes
4) Haloalkanes
5) Alcohols
6) Carboxylic acids
7) Esters
8) Aldehydes
9) Ketones

Each of these homologous series has it's own **functional group**.

Definition: Functional group: A bond or an atom or a group of atoms that determine(s) the physical and chemical properties of a group of organic compounds.

Organic molecules

Definition: hydrocarbons: Organic compounds that consist of hydrogen and carbon only.

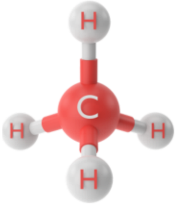
There are three types of hydrocarbons:

1. Alkanes
2. Alkenes
3. Alkynes

Did you know?

The names all start with the prefix Al – as these are **aliphatic hydrocarbons**

Alkanes



Alkanes are hydrocarbons that have **SINGLE** bonds between carbon atoms only.

The table below represents the IUPAC name, structural formula and condensed structural formula for the first eight **straight - chained alkanes**:

Number of carbon atoms (*n*)	Prefix	Name	Molecular formula	Condensed structural formula
1	Meth-	Methane	CH_4	CH_4
2	Eth-	Ethane	C_2H_6	CH_3CH_3
3	Prop-	Propane	C_3H_8	$CH_3CH_2CH_3$
4	But-	Butane	C_4H_{10}	$CH_3CH_2CH_2CH_3$
5	Pent-	Pentane	C_5H_{12}	$CH_3CH_2CH_2CH_2CH_3$
6	Hex-	Hexane	C_6H_{14}	$CH_3CH_2CH_2CH_2CH_2CH_3$
7	Hept-	Heptane	C_7H_{16}	$CH_3CH_2CH_2CH_2CH_2CH_2CH_3$
8	Oct-	Octane	C_8H_{18}	$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_3$

IUPAC is the **International Union of Pure and Applied Chemistry.**

All organic molecules are named according to the IUPAC nomenclature,

All the organic molecules listed above belong to the same homologous series, namely **alkanes**.

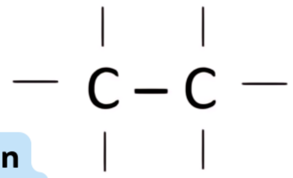
NOTE:

- The suffix **-ane** indicates that the organic molecule is an alkane.
- Moving from one alkane to the next, the chemical formula differs by a CH_2 group.

Structure of alkanes

Functional group of alkanes: Alkanes are characterised by single bonds between carbon atoms and therefore the functional group is a single bond between two carbon atoms.

Structure of the functional group of alkanes:



NOTE: Every carbon atom must have FOUR BONDS to form a stable molecule.

PRO-TIPS

The structure of the functional group simply shows the **bond** between the **carbon** atoms and the bond lines, but it does **NOT** show other atoms bonded, as these can be carbon or hydrogen atoms.

- **General formula** for alkanes is C_nH_{2n+2}

Where n = 1, 2, 3... (the number of carbon atoms)

IUPAC (International Union of Pure and Applied Chemistry) nomenclature of naming alkanes with straight and branched chains

- Alkanes are examples of **saturated compounds,** containing the maximum number of hydrogen atoms.

Definition: Saturated compounds: Compounds in which there are no multiple bonds between C (carbon) atoms in their hydrocarbon chains.

Rules for naming straight - chained alkanes

1. Identify the longest, continuous chain - this can be a straight chain or a bent chain.
2. Identify the number of carbon atoms in the longest, continuous chain.
3. Using IUPAC nomenclature, name the straight- chained alkane.

Example:

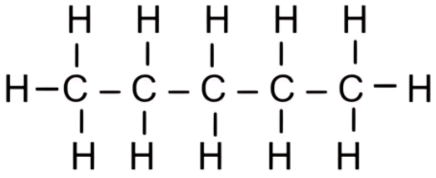


Figure 1

NOTE: This is the **structural formula,** which shows all the bond lines.

- **Homologous series:** Figure 1 above represents an alkane, as there are only single bonds between the carbon atoms.
- This is a straight chained alkane, with no branches (or side chains). There are 5 carbon atoms in the straight chain, therefore the IUPAC name of this alkane is: **pentane**.

Rules for naming branched chained alkanes

Branches (side chains or substituents)

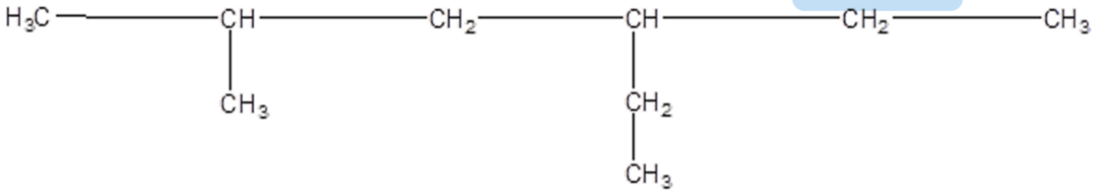
Alkyl substituent	Alkyl substituent name
CH_3-	**Methyl**
C_2H_5-	**Ethyl**
C_3H_7-	Propyl
C_4H_9-	Butyl
C_5H_{11}-	Pentyl
C_6H_{13}-	Hexyl
C_7H_{15}-	Heptyl
C_8H_{17}-	Octyl

NOTE:

- Alkyl substituents have one less hydrogen atom then the corresponding alkane.
- methyl and ethyl substituents are the most commonly encountered substituents.

Example:

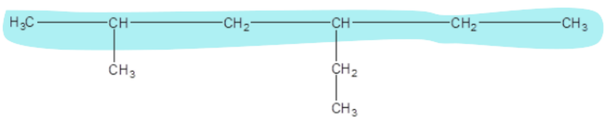
NOTE: This is the semi - condensed **structural formula,** which shows some of the bond lines.



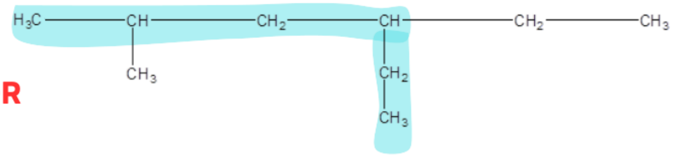
$H_3C-CH(CH_3)-CH_2-CH(CH_2-CH_3)-CH_2-CH_3$

Step 1: Note the bonds between the carbon atoms. If there are only single bonds between the carbon atoms, the organic molecule is an **alkane**.

Step 2: Select the longest continuous carbon chain (it can be a bent chain). This is called the parent chain.

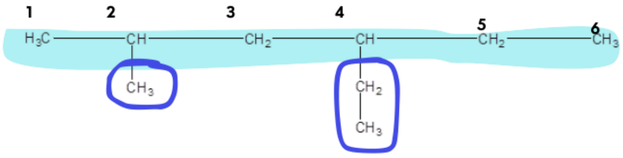


OR

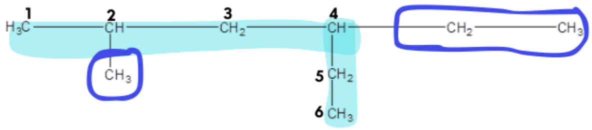


In the example, the parent chain has 6 carbon atoms, therefore, it is **hexane**. (Remember the suffix of the alkanes is –ane)

Step 3: Identify the substituents (side chains/branches) and number the parent chain such that the substituents are allocated **lower numbers.**



OR



NOTE:

- In the example, numbering from **left to right**, the substituents end up on carbon 2 and 4.
- Whereas, numbering from **right to left**, the substituents end up on carbon 3 and 5.
- Therefore, the lower numbers occur when we number from left to right, this is the correct numbering.

Step 4: Name the substituents (side chains), including their position on the parent chain. In this example, the side chains are: 2 - methyl and 4 - ethyl

Step 5: Name the organic compound. The name of the compound starts with substituents (side chains) in **alphabetical order**, followed by the name of the **parent chain**. The correct IUPAC name for the example is 4- ethyl-2-methylhexane.

NOTE:

- In IUPAC nomenclature:
- A hyphen (-) separates numbers from words
- A comma (,) separates numbers from numbers.
- There is no space between the words that make up the name. Marks will be lost if the hyphen or comma is omitted.

Another step is required if the same substituent (side chain) occurs two or more times:

Step 6: If the same substituent occurs more than once in the molecule, the prefix “di”, “tri”, “tetra”, and so on are used to indicate how many times it occurs.

Remember di = 2, tri= 3, tetra = 4.
If the substituent (side chain) occurs twice on the **same** carbon atom, the number to indicate the position of the substituent (side chain) is **repeated,** for example: **2,2 - di**methyl.

NOTE: When writing IUPAC names, substituents are written in alphabetical order (e.g., bromo, chloro, ethyl, methyl). The prefixes di- , tri-, and tetra- do not take alphabetical preference i.e. they are not alphabetised.

Worked examples

Multiple choice questions

C + A

1.1 To which homologous series does the organic molecule shown below belong?

$CH_3CH_2CH_2CH_3$

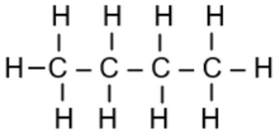
A Alkanes
B Alkenes
C Alkynes
D Functional group

PRO-TIPS

- If the condensed structural formula is given, draw the structural formula to see the bond lines.
- All multiple choice questions are two marks

Answer: A

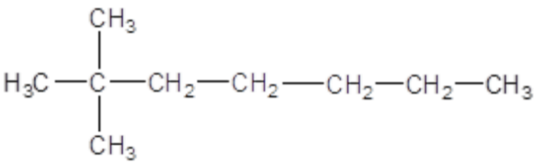
Draw the structural formula:



$\mathrm{H{-}C{-}C{-}C{-}C{-}H}$

Note:
- There are only **single bonds** between the carbon atoms.
- Therefore the homologous series (‘organic molecule family’) to which this organic molecule belongs is **alkanes**.

1.2 Which ONE of the following represents the IUPAC name and molecular formula of the following molecule?



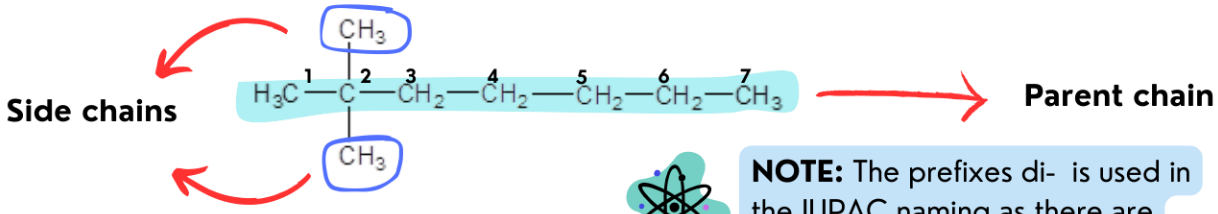
$$H_3C-\overset{\displaystyle CH_3}{\underset{\displaystyle CH_3}{C}}-CH_2-CH_2-CH_2-CH_2-CH_3$$

	IUPAC name	**Molecular formula**
A	6,6 -dimethylheptane	C_9H_{20}
B	2-methyloctane	C_8H_{18}
C	2-dimethylheptane	C_9H_{20}
D	2,2-dimethylheptane	C_9H_{20}

Answer: D

Determine the IUPAC name:

1. Identify the longest flowing chain, i.e., parent chain
2. Identify the side chains (substituents).
3. Number the carbon atoms in the parent chain such that the side chains (substituents) end up on the lower numbers.



NOTE: The prefixes di- is used in the IUPAC naming as there are TWO methyl side chains (substituents). The position of both the side chains must be indicated, even if they are both on the same carbon atom.

IUPAC name: 2,2 - dimethylheptane

Molecular formula:

To determine the molecular formula:

1. Count the total number of carbon atoms in the molecule.
2. Use the general formula to determine the number of hydrogen atoms.
   OR
   Count the total number of hydrogen atoms in the molecule.

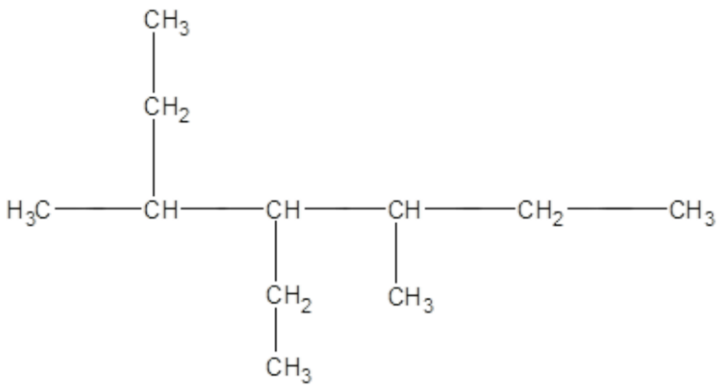
General formula for alkanes: C_nH_{2n+2}

Molecular formula for 2,2 -dimethylheptane: $C_9\ H_{2(9)+2}$

Molecular formula for 2,2 -dimethylheptane: C_9H_{20}

Worked example

1. An organic molecule is represented below.



1.1 Write down the homologous series to which the above organic molecule belongs. Give a reason for the answer. (2)

1.2 Write down the IUPAC name of the above organic molecule. (3)

1.3 Write down the empirical formula of the above organic molecule. (2)

1.4 Write down the condensed structural formula of the above organic molecule. (2)

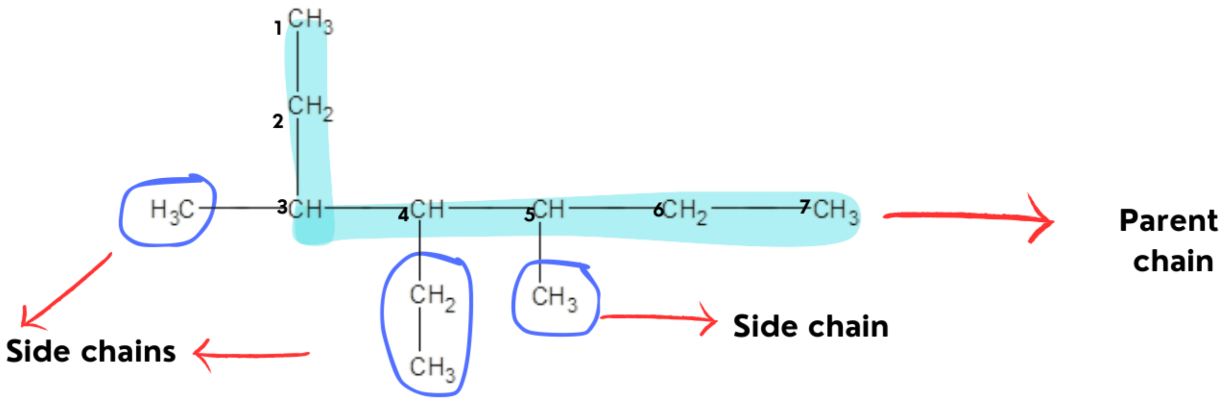
Another organic molecule 2,2,4 - trimethyloctane has the same molecular formula as the organic molecule above.

1.5 Write down the structural formula of 2,2,4 -trimethyloctane. (2)

1.1 Alkanes. There are only single bonds between the carbon atoms.

1.2 **Determine the IUPAC name:**

1. Identify the longest flowing chain, i.e., parent chain
2. Identify the side chains (substituents).
3. Number the carbon atoms in the parent chain such that the side chains (substituents) end up on the lower numbers.



IUPAC name: 4-ethyl-3,5- dimethylheptane

1.3 Before determining the empirical formula, the molecular formula must be determined:

Molecular formula: C_nH_{2n+2}
Molecular formula: $C_{11}H_{2(11)+2}$
Molecular formula: $C_{11}H_{24}$
∴ Empirical formula: $C_{11}H_{24}$

NOTE: The empirical formula is the chemical formula that shows the simplest whole - number ratio of atoms in a compound. The empirical formula can be the same as the molecular formula.

NOTE: In this example, the molecular formula represents the simplest whole number ratio in which the carbon and hydrogen atoms bond, therefore, the empirical formula and molecular formula are the same.

1.4

NOTE: How to write the condensed structural formula

- When writing the condensed structural formula, start at carbon **1,** and follow through with summarising the number of hydrogen atoms bonded to carbon 2, 3 etc
- The side chains (or substituents) are represented in brackets in the condensed structural formula - note CH_3 = methyl, CH_2CH_3 = ethyl
- If the carbon chain repeats, this can be represented in brackets, with a subscript representing the carbon chain repeating.

$CH_3CH_2CH(CH_3)CH(CH_2CH_3)CH(CH_3)CH_2CH_3$

methyl side chain on carbon 3

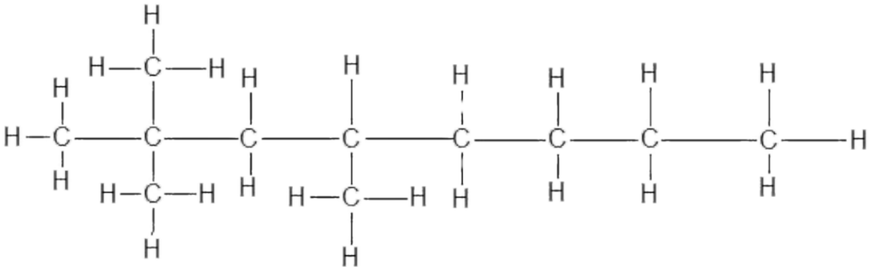
methyl side chain on carbon 5

ethyl side chain on carbon 4

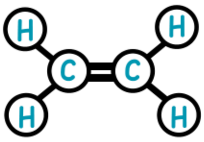
1.5

NOTE: When drawing the structural formula:

- Draw the structure in pencil.
- When drawing the structural formula, start by drawing the parent chain, number the parent chain and draw the side chains (substituents).
- All the bond lines must be drawn.
- Make sure that every carbon has 4 bonds.



Alkenes



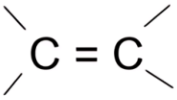
Alkenes are hydrocarbons that have at least **ONE DOUBLE BOND** between the carbon atoms in their hydrocarbon chains.

NOTE:

- The double bond is the functional group of an alkene.
- Each carbon atom must have four bonds to form a stable molecule.

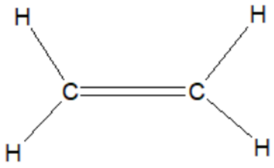
Functional group of alkenes

Structural formula of the functional group for alkenes:



General formula for alkenes: C_nH_{2n} .
Where n = 1, 2, 3... i.e., the number of carbon atoms in the hydrocarbon chain.

The simplest alkene is **ethene**, which consists of two carbon atoms, and a double bond between the carbon atoms. The structural formula of ethene is shown in **figure 2** below:



Molecular formula of ethene: C_2H_4

Figure 2

- Alkenes are examples of **unsaturated compounds**, because of the double bond between the carbon atoms.

Definition: Unsaturated compounds: Compounds with one or more multiple bonds between C (carbon) atoms in their hydrocarbon chains.

IUPAC nomenclature: Naming alkenes with straight and branched chains

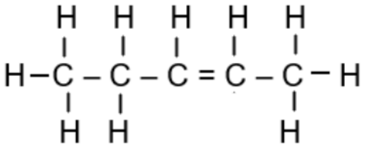
Rules for naming straight - chained alkenes

1. Identify the double bond between the carbon atoms. (Note that the homologous series is an **alkene**)
2. Identify the longest, continuous chain containing the double bond- this can be a straight chain or a bent chain.
3. Identify the number of carbon atoms in the longest, continuous chain.
4. Number the continuous chain (if there are four or more carbon atoms in the chain), such that the functional group (i.e., the double bond) ends up on the lower position.
5. Using IUPAC nomenclature, name the straight- chained alkene, indicating the position of the function group (double bond), where necessary. **NOTE:** When naming alkenes, the suffix -ane (from an alkane) changes to -ene (for an alkene)

PRO-TIPS

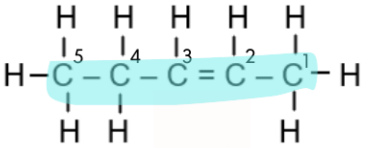
The position of the functional group (i.e., the double bond) must **only be indicated if its position can change**. This is only necessary when there are four or more carbon atoms in the hydrocarbon chain.

Example: Write down the IUPAC name of the organic molecule below:



NOTE:
Homologous series: This organic molecule is an alkene, because of the double bond between the carbon atoms.

1. Identify the long, continuous chain containing the functional group, i.e., the double bond.
2. Number the chain such that the double bond ends up on the lower carbon atom.
   In this example, this is from right to left:

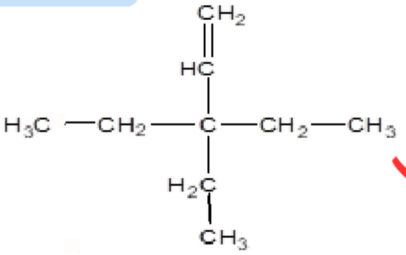


3. Note the number of carbon atoms in the hydrocarbon chain:
   In this example there are 5 carbon atoms in the hydrocarbon chain, therefore, the parent chain has the prefix **pent-**
4. The double bond lies between carbon 2 and carbon 3. The position of the double bond is always on the lower carbon, therefore it will be on carbon 2. This must be indicated in the IUPAC name, after the prefix (i.e., **pent-**), but before the suffix **- ene**:

IUPAC name: pent - 2 - ene

Rules for naming branched chained alkenes (with side chains or substituents)

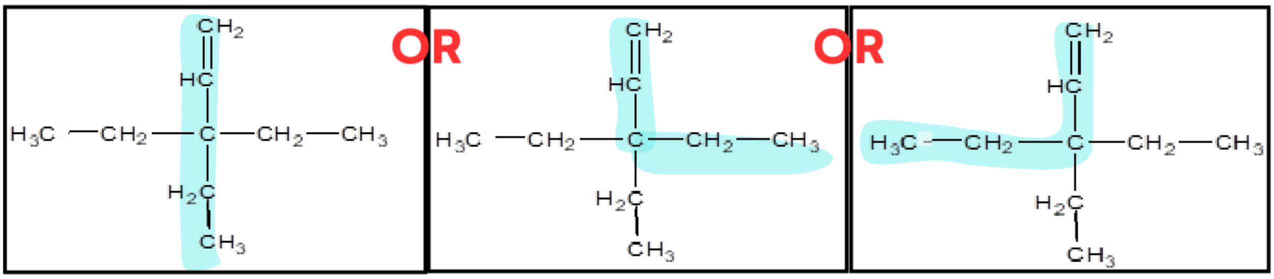
Example:



NOTE: This is the **semi - condensed structural formula,** which shows some, but not all of the bond lines.

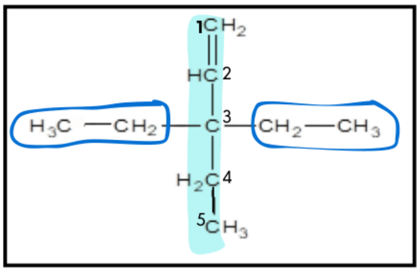
Step 1: Note the bonds between the carbon atoms. If there is a double bond between the carbon atoms, this indicates that that organic molecule is an alkene.

Step 2: Select the longest continuous carbon chain **containing the double bond** (it can be a bent chain). This is called the parent chain.



In this example, there are 5 carbon atoms in the parent chain, therefore the prefix **pent -** is used.

Step 3: Number the longest chain such that the functional group, i.e., the **double bond** (C = C) ends up on the lower position/number. Note the substituents, **and where possible**, number the parent chain such that the double bond and the substituents end up on the lower carbon atoms.



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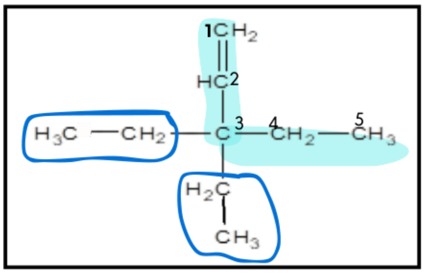

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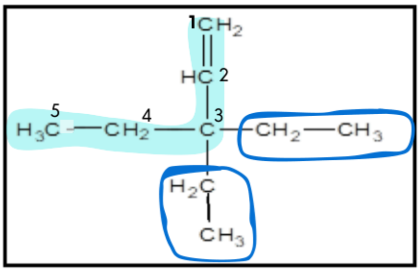


Step 4: Identify and name the substituents (side chains). The substituents (side chains) acquire the position or number of the carbon atom to which they are attached.

NOTE: The functional group (i.e., double bond) ending up on the lower carbon takes preference over the position of the substituents or side chains.

In this example, the double bond lies between carbon 1 and carbon 2, therefore it will take on **position 1.** This is named as pent - 1 - ene.
There are two ethyl side chains on carbon 3, note that the prefix di - is used to indicate that there are two ethyl side chains and the position of both ethyl side chains must be indicated in the IUPAC name.

Step 5: Name the organic compound. The name of the compound starts with substituents (side chains) in alphabetical order, followed by the name of the parent chain containing the double bond.The correct IUPAC name for the example is **3,3 - diethylpent-1-ene**

NOTE:
- In IUPAC nomenclature:
- A hyphen (-) separates numbers from words
- A comma (,) separates numbers from numbers.
- There is no space between the words that make up the name. Marks will be lost if the hyphen or comma is omitted.

Worked example

1. An organic molecule is represented below:

$$CH_2C(CH_2CH_3)CH(CH_2CH_3)(CH_2)_2CH_3$$

1.1 Draw the structural formula of the organic molecule. (2)

1.2 Write down the homologous series to which the above organic molecule belongs. Give a reason for the answer. (2)

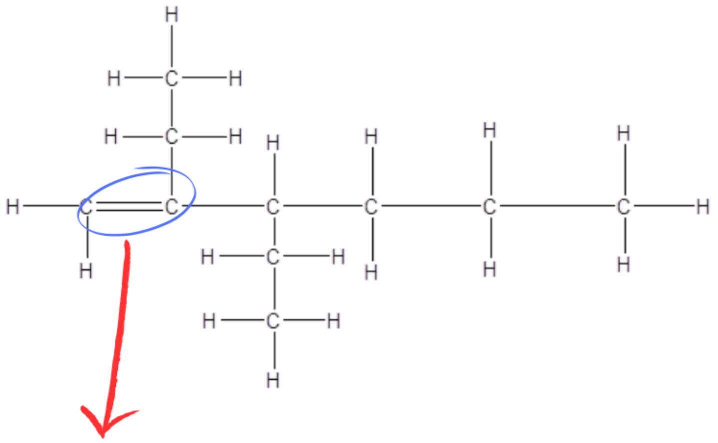
1.3 Write down the IUPAC name of the above organic molecule. (3)

1.4 Write down the molecular formula of the above organic molecule. (2)

1.1

When drawing the structural formula from the condensed structural formula, the following procedure must be followed:

- Start by drawing the carbon atoms, in order, as given by the condensed structural formula, followed by the hydrogen atoms. **Check that every carbon has four bonds** - if there is less than four bonds, this indicates that there is a double or triple bond between the carbon atoms.
- The side chains are in brackets, and are bonded to the carbon atom preceding (in front of) the bracket. Note that CH_2 indicated in brackets is not a side chain, but a repeat of the CH_2 group.
- Always double check that the number of carbon and hydrogen atoms in the structural formula against the number of carbon and hydrogen atoms in the condensed structural formula.

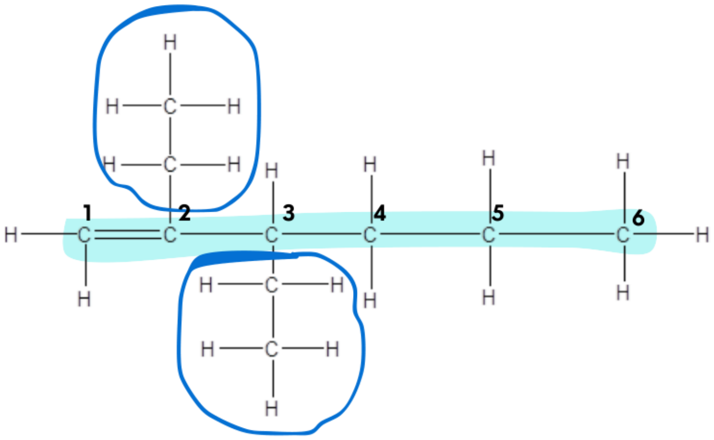


Note the double bond between carbon 1 and carbon 2

1.2 Alkenes. There is a double bond between two carbon atoms, namely carbon 1 and carbon 2.

1.3 **Determine the IUPAC name:**

1. Identify the longest flowing chain, i.e., parent chain containing the functional group (i.e., the double bond). In this example, this is hex - 1 - ene.
2. Identify the side chains (substituents). In this example, there are two ethyl side chains.
3. Number the carbon atoms in the parent chain such that the functional group (i.e., the double bond) ends up on the lower position or lower carbon atom in the parent chain. In this example, the ethyl side chains are on carbon 1 and 2, namely 2,3 - diethyl



IUPAC name: 2,3 - diethylhex-1-ene

1.4 The molecule is an alkene, therefore the general formula for alkenes is $C_n H_{2n}$
There are 10 atoms in total in this alkene, therefore, the molecular formula is:
$C_{10}H_{20}$

C_nH_{2n}

PRO-TIPS

Always double check the molecular formula by physically counting the number of hydrogen (and of course carbon atoms) in the organic molecule.

REMINDER :QUESTION DIFFICULTY

C

COMPREHENSION AND RECALL QUESTIONS

These are common questions which include definitions and calculation questions that look similar to the questions covered in class. Approximately **50%** of Paper 1 (Physics) will include questions on this level.

A

ANALYSIS AND APPLICATION QUESTIONS

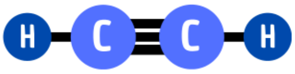
These are more complex questions which involves applying the knowledge and skills learned in this chapter. Approximately **40%** of Paper 1 (Physics) will include questions on this level.

P

PROBLEM- SOLVING QUESTIONS

These are questions that require critical thinking and being able to make connections between different representations of information and integrating different topics. They are not familiar questions, but are able to be solved through critical analysis. Approximately **10%** of Paper 1 (Physics) will include questions on this level.

Alkynes



Alkynes are hydrocarbons that have at least **ONE TRIPLE BOND** between the carbon atoms in their hydrocarbon chains.

Functional group of alkynes

Structural formula of the functional group for alkynes:

$$-C \equiv C-$$

NOTE:
- The triple bond is the functional group of an alkyne.
- Each carbon atom must have four bonds to form a stable molecule.

General formula for alkenes: C_nH_{2n-2}
Where n = 1, 2, 3... i.e., the number of carbon atoms in the hydrocarbon chain.

The simplest alkyne is **ethyne**, which consists of two carbon atoms, and a triple bond between the carbon atoms. The structural formula of ethene is shown in **figure 3** below:

$$H-C \equiv C-H$$

Molecular formula of ethyne: C_2H_2

Figure 3

- Alkynes, like alkenes, are examples of **unsaturated compounds**, because of the triple bond between the carbon atoms.

Definition: Unsaturated compounds: Compounds with one or more multiple bonds between C (carbon) atoms in their hydrocarbon chains.

IUPAC nomenclature: naming alkynes with straight and branched chains

Rules for naming straight - chained alkynes

1. Identify the triple bond between the carbon atoms. (Note that the homologous series is an **alkyne**)
2. Identify the longest, continuous chain containing the triple bond- this can be a straight chain or a bent chain.
3. Identify the number of carbon atoms in the longest, continuous chain.
4. Number the continuous chain (if there are four or more carbon atoms in the chain), such that the functional group (i.e., the triple bond) ends up on the lower position.
5. Using IUPAC nomenclature, name the straight- chained alkyne, indicating the position of the functional group (triple bond), where necessary.

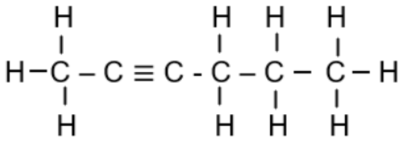
PRO-TIPS

The position of the functional group (i.e., the triple bond) must **only be indicated if its position can change**. This is only necessary when there are four or more carbon atoms in the hydrocarbon chain.

NOTE: When naming alkynes, the suffix -ane (from an alkane) changes to -yne (for an alkyne)

Example:

Write down the IUPAC name of the organic molecule below:



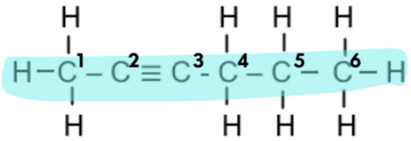
$H-C-C\equiv C-C-C-C-H$

NOTE:
Homologous series: This organic molecule is an alkyne, because of the triple bond between the carbon atoms.

PRO-TIPS

Naming an alkyne is very similar to naming an alkene - the only difference is in an alkyne, the suffix - yne is used to indicate the homologous series.

1. Identify the long, continuous chain containing the triple bond.
2. Number the chain such that the triple bond ends up on the lower carbon atom. In this example, this is from left to right:



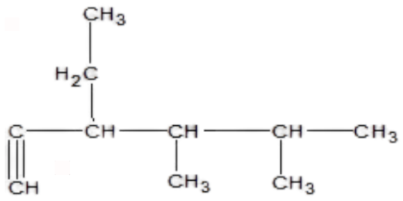
$H-C^1-C^2\equiv C^3-C^4-C^5-C^6-H$

3. Note the number of carbon atoms in the hydrocarbon chain: In this example, there are 6 carbon atoms in the hydrocarbon chain, therefore, the parent chain has the prefix **hex-**
4. The triple bond lies between carbon 2 and carbon 3. The position of the triple bond is always on the lower carbon, therefore it will be on carbon 2. This must be indicated in the IUPAC name, after the prefix (i.e., **hex-**,) but before the suffix **- yne**:

IUPAC name: hex - 2 - yne

Rules for naming branched chained alkynes (with side chains or substituents)

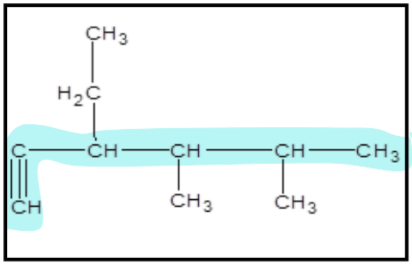
Example:



NOTE: This is the **semi - condensed structural formula,** which shows some, but not all of the bond lines.

Step 1: Note the bonds between the carbon atoms. If there is a triple bond between the carbon atoms, this indicates that the organic molecule is an alkyne.

Step 2: Select the longest continuous carbon chain **containing the triple bond** (it can be a bent chain). This is called the parent chain.



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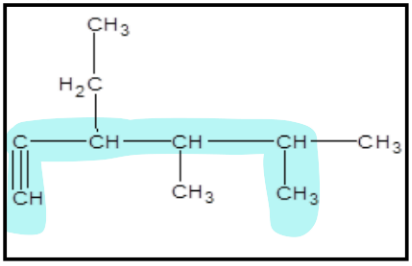
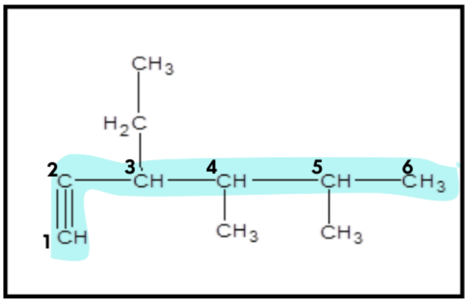


In this example, there are 6 carbon atoms in the parent chain, therefore the prefix **hex -** is used.

Step 3: Number the longest chain such that the functional group i.e., the **triple bond** (C ≡C) ends up on the lower position/number. Note the substituents, **and where possible**, number the parent chain such that the functional group (i.e., triple bond) and the substituents end up on the lower carbon atoms.



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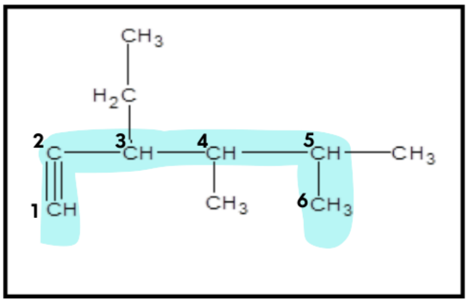


Step 4: Identify and name the substituents (side chains). The substituents (side chains) acquire the position or number of the carbon atom to which they are attached.

NOTE: The functional group (i.e., triple bond) ending up on the lower carbon takes preference over the position of the substituents or side chains.

In this example, the triple bond lies between carbon 1 and carbon 2, therefore it will take on **position 1.** This is named as hex - 1 - yne.
There is one ethyl side chain on carbon 3, and two methyl side chains on carbon 4 and carbon 5.

NOTE: the prefix di - is used to indicate that there are two methyl side chains and the position of both methyl side chains must be indicated in the IUPAC name. The prefix di - does **NOT** take alphabetical preference.

Step 5: Name the organic compound. The name of the compound starts with substituents (side chains) in alphabetical order, followed by the name of the parent chain containing the double bond.The correct IUPAC name for the example is **3 - ethyl - 4,5 - dimethylhex-1-yne.**

NOTE:
The prefix di - does NOT take alphabetical preference.

NOTE:
In IUPAC nomenclature:
A hyphen (-) separates numbers from words
A comma (,) separates numbers from numbers.
There is no space between the words that make up the name.
Marks will be lost if the hyphen or comma is omitted.

Worked examples

Multiple choice questions

1. Which ONE of the following organic molecules represents a SATURATED COMPOUND?

A C_4H_8

B C_4H_6

C C_4H_{10}

D C_5H_8

Answer: C

Alkanes are examples of saturated compounds. Alkanes have the general formula C_nH_{2n+2}
This matches option C, since the number of carbon atoms, n = 4
C_nH_{2n+2}
$C_4H_{2(4)+2}$
C_4H_{10}

Option A: This is an alkene, with the general formula C_nH_{2n} . Alkenes are unsaturated compounds.
Option B: This is a alkyne, with the general formula C_nH_{2n-2} . Alkynes are unsaturated compounds.
Option D: This is an alkyne, with the general formula C_nH_{2n-2} . Alkynes are unsaturated compounds.

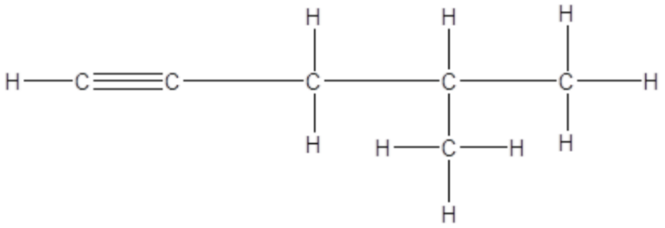
2. An organic molecule is represented below:

$CHCCH_2CH(CH_3)CH_3$

	IUPAC name	Empirical formula
A	3-methylbut-1-ene	C_3H_{10}
B	4-methylpent-1-yne	C_6H_{10}
C	2-methylpent-4-yne	C_3H_5
D	4- methylpent-1-yne	C_3H_5

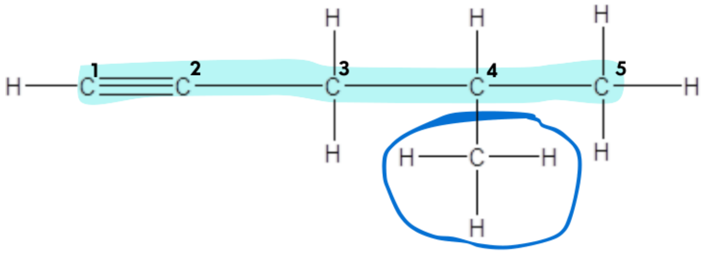
Answer: D

✓ **Draw the structural formula of the organic molecule**. Remember that every carbon atom must have four bonds - this can be used to determine whether the organic molecule has single bonds only between carbon atoms or whether it also has a double **or** triple bond/s between the carbon atoms.This organic molecule has a triple bond between the carbon atoms and is therefore an alkyne.



✓ **Determine the IUPAC name of the alkyne:**

1. Identify the longest flowing chain, i.e., parent chain containing the functional group (i.e., the triple bond).
   In this example, there are 5 carbon atoms in the parent chain and the triple bond lies between carbon 1 and 2. The parent chain is pent - 1 - yne.
2. Identify the side chains (substituents).
   In this example, there is a methyl side chain.
3. Number the carbon atoms in the parent chain such that the functional group (i.e., the triple bond) ends up on the lower position or lower carbon atom in the parent chain. In this example, the methyl side chain is on carbon 4.



IUPAC name: 4 - methylpent - 1 - yne

✓ **Determine the molecular formula of the alkyne**

General formula for alkynes: C_nH_{2n-2}

$C_6H_{2(6)-2}$

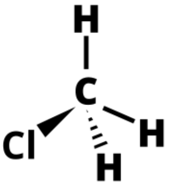
C_6H_{10} → **This is the molecular formula**

NOTE: The empirical formula is the chemical formula that shows the simplest whole - number ratio of atoms in a compound.
The empirical formula can be the same as the molecular formula.

To determine the **empirical formula**, simplify the ratio in which the carbon and hydrogen atoms bond, this can be simplified by dividing by 2 throughout:

Empirical formula: $\mathbf{C_3H_5}$

Haloalkanes



The prefix ‘**halo**’ in haloalkanes means halogens. Halogens are group VII or group 17 elements, namely fluorine (F), chlorine (Cl), bromine (Br) and iodine (I).

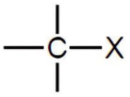
What are haloalkanes?

Haloalkanes are derived from alkanes. When an alkane is reacted with a halogen molecule (through a substitution reaction), a haloalkane is produced.

Functional group of haloalkanes

Haloalkanes are characterised by one or more halogen atoms. The halogen atom(s) in a haloalkane are both the functional group and the substituent of a haloalkane.

Structural formula of the functional group for haloalkanes:



(X = F, Cℓ, Br, I)

- **General formula** for haloalkanes is $C_nH_{2n+1}X$

Where n = 1, 2, 3… (the number of carbon atoms)
X = halogen atom (F or Cl or Br or I)

NOTE: This is produced only if one hydrogen atom was replaced by a halogen **X**.

NOTE: Haloalkanes are restricted to **two** functional groups in a compound.

IUPAC (International Union of Pure and Applied Chemistry) nomenclature of naming haloalkanes with straight and branched chains:

IUPAC naming of halogen substituents (side chains) that occur on the alkane chains:

F- fluoro
Cl – chloro
Br- bromo
I- iodo

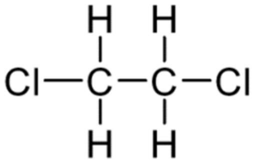
The haloalkanes are named in a similar way that the alkanes are named.
Step 1: Select the longest, continuous carbon chain (even if it is bent). This is the parent chain. The parent chain must contain the halogen substituents and is chosen so that the substituents (both halogen and alkyl substituents) are assigned the lower numbers.
Step 2: The halogens are treated as substituents (side chains) in the same way as alkyl groups are and are also placed in alphabetical order.

NOTE:
If **both** halogen and alkyl groups are substituents, they are placed in **alphabetical** order and the halogen atoms do not get preference over alkyl groups.
When substituents, e.g. Br and Cℓ or Cℓ and methyl, have the **same number** when numbered from different ends of chain, preference is given to alphabetical order,e.g. bromo- over chloro-; chloro- over methyl-.
When writing IUPAC names, substituents are written alphabetically namely bromo, chloro, ethyl, methyl. **Ignore** prefixes di and tri.

Worked example

1. Organic molecules **A** and **B** are represented below:

A



B 4-chloro-3,3-dimethylhexane

1.1 Write down the functional group in organic molecule **A** and **B**. (1)

1.2 Write down the IUPAC name of organic molecule **A.** (2)

1.3 Write down the structural formula of organic molecule **B.** (2)

1.4 Write down the molecular formula of molecule **A.** (2)

1.5 One of the methyl side chains in molecule **B** is replaced by a bromine atom. Write down the new IUPAC name of molecule **B**. (3)

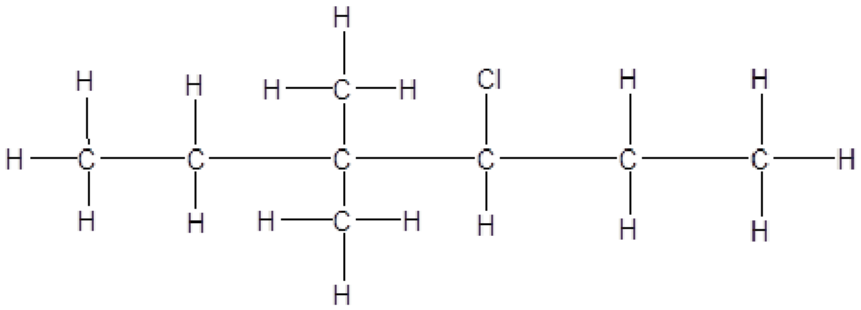
1.1 The functional group of a haloalkane is the **halogen atom.** This is also a substituent (side chain).

∴The halogen atoms or the chlorine atoms.

1.2 1,2 -dichloroethane.

NOTE: In the IUPAC naming of this organic molecule, the position of both halogen atoms (i.e., the chlorine atoms) must be indicated, as it is possible for both chlorine atoms to be bonded to the same carbon atom

1.3



NOTE: When drawing the structural formula:

- Draw the structure in pencil.
- When drawing the structural formula, start by drawing the parent chain, number the parent chain and draw the side chains(substituents).
- All the bond lines must be drawn.
- Make sure that every carbon has 4 bonds.

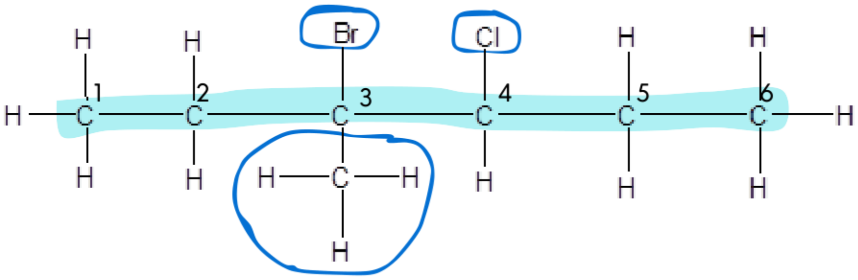
1.4 The molecular formula follows the following order:

- Number of carbon atoms.
- Number of hydrogen atoms.
- Number of halogen atoms.

∴ $C_2H_4Cl_2$

1.5 **Tips to approaching the question:**

Redraw of the structure of the molecule, replacing one of the methyl side chains with a bromine atom:



Step 1: Identify the longest, continuous chain. This is the parent chain. In this example, this is **hexane.**

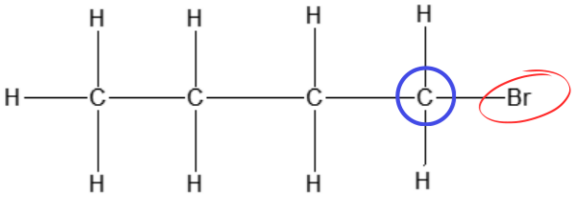
Step 2: Number the parent chain, such that the substituents end up on the lower positions on the carbon atoms. Numbering from left to right will result in bromine ending up on the lower position than the chlorine atom, this is required according to IUPAC naming rules of haloalkanes.

IUPAC name of molecule **B**: 3 - bromo - 4 - chloro - 3 - methylhexane

Primary, secondary and tertiary haloalkanes

1. Primary haloalkanes

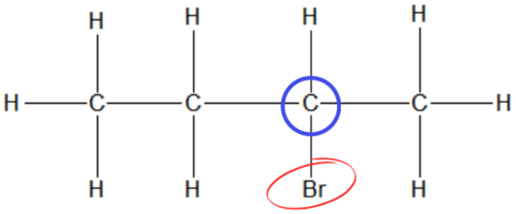
Example: 1 – bromobutane



In primary (1°) haloalkanes, the carbon to which the halogen (X) is bonded, is bonded to **ONE** other carbon atom.

2. Secondary haloalkanes

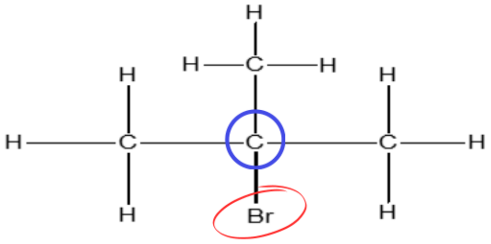
Example: 2 – bromobutane



In secondary (2°) haloalkanes, the carbon to which the halogen (X) is bonded, is bonded to **TWO** other carbon atoms.

3. Tertiary haloalkanes

Example: 2 – bromo – 2 – methylpropane



In tertiary (3°) haloalkanes, the carbon to which the halogen (X) is bonded, is bonded to **THREE** other carbon atoms.

Worked example

Multiple choice question

C + A

1.1 Which ONE of the following represents a SECONDARY haloalkane?

A CH_3CHFCH_3

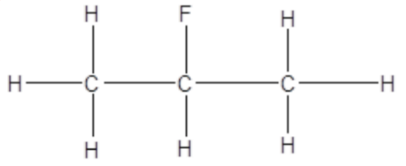
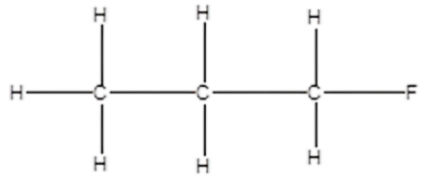
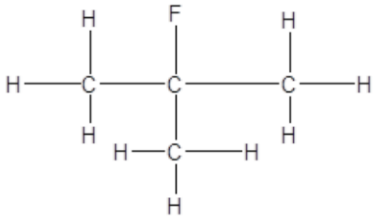
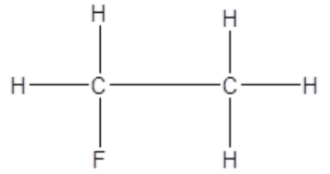
B $CH_3CH_2CH_2F$

C $CH_3CF(CH_3)CH_3$

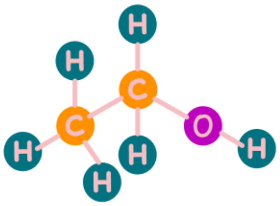
D CH_2FCH_3

Answer: A

The condensed structural formula is given. Draw the structure of each of the molecules and analyse each of the molecules, to determine if the molecule is a primary, secondary or tertiary haloalkane.

A ✓  Secondary haloalkane. The carbon to which the halogen is bonded, is bonded to two other carbon atoms.	B ✗  Primary haloalkane. The carbon to which the halogen is bonded, is bonded to one other carbon atom.
C ✗  Tertiary haloalkane. The carbon to which the halogen is bonded, is bonded to three other carbon atoms.	D ✗  Primary haloalkane. The carbon to which the halogen is bonded, is bonded to one other carbon atom.

Alcohols

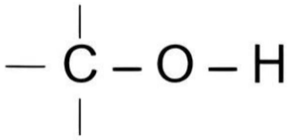


Alcohols are organic molecules that are characterised by one or more **–OH** groups (hydroxyl groups) attached to a saturated carbon atom.

Functional group of alcohols

NOTE: The name of the homologous series alc**OH**ols has the hydroxyl group in the name.

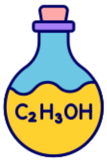
Structural formula of the functional group for alcohols:



$$\begin{array}{c} | \\ -\mathrm{C}-\mathrm{O}-\mathrm{H} \\ | \end{array}$$

Condensed structural formula of the functional group for alcohols:

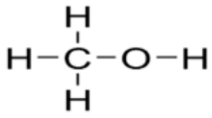
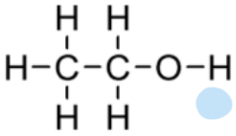
-OH Hydroxyl group



Name of functional group of alcohols:

Examples of alcohols

The table below represents the IUPAC name, structural formula and molecular formula of the two simplest alcohols.

IUPAC name	Structural formula	Molecular formula
Methanol	 $\begin{array}{c}\mathrm{H}\\ \mid\\ \mathrm{H-C-O-H}\\ \mid\\ \mathrm{H}\end{array}$	CH_3OH
Ethanol	 $\begin{array}{c}\mathrm{H\ \ H}\\ \mid\ \ \mid\\ \mathrm{H-C-C-O-H}\\ \mid\ \ \mid\\ \mathrm{H\ \ H}\end{array}$	C_2H_5OH

General formula of alcohols containing one hydroxyl functional group:

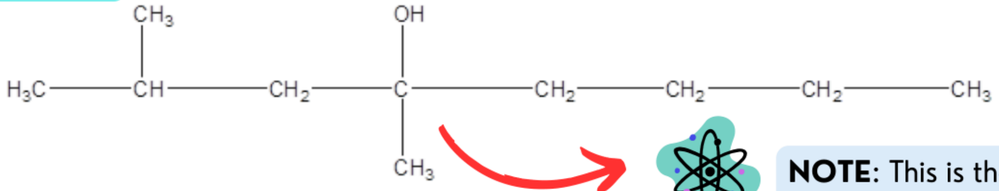
$$C_nH_{2n+1}OH$$

PRO-TIPS

The IUPAC naming of alcohols:
- the **prefix** meth -, eth-, prop - etc. represents the **number** of **carbon** atoms in the hydrocarbon chain.
- There are **single** bonds between the carbon atoms in an **alcohol**, therefore the prefix is followed by -**an** (derived from an alkane)
- The suffix -ol indicates that the **organic** molecule is an alcohol.

Naming alcohols: IUPAC nomenclature of alcohols

Example

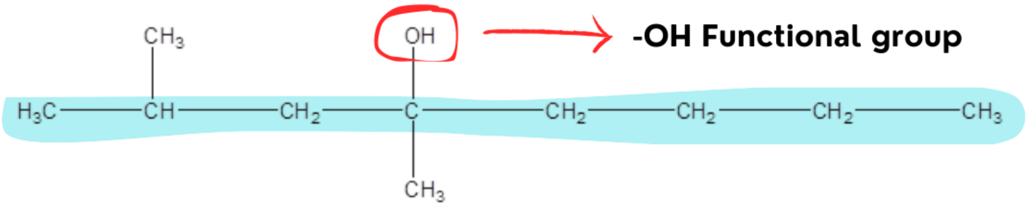


$H_3C-CH(CH_3)-CH_2-C(OH)(CH_3)-CH_2-CH_2-CH_2-CH_3$

NOTE: This is the **semi - condensed structural formula,** which shows some, but not all of the bond lines.

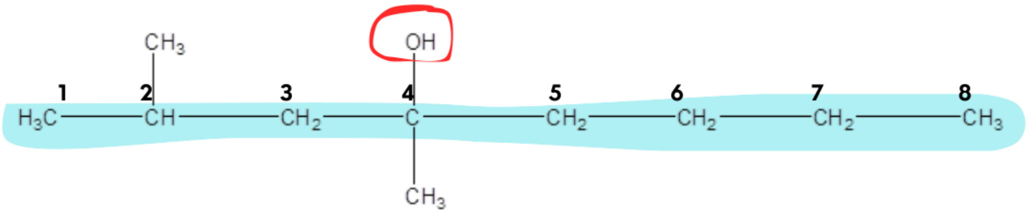
Step 1: Check that there is an –OH functional group present. If the molecule has an -OH functional group, the molecule is an alcohol.

Step 2: Select the longest continuous carbon chain containing the –OH group. This is the parent chain. In the example the organic molecule has eight carbon atoms. The prefix oct- is used in the IUPAC name.

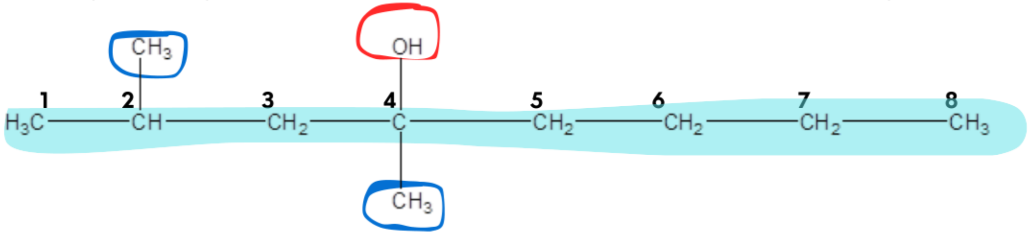


-OH Functional group

Step 3: Number the parent chain so that the carbon atom to which the functional group (–OH group) is bonded has the lower number. If the chain is numbered from left to right, the –OH group is at carbon number 4. If it is numbered from right to left, the –OH group is at carbon atom number 5. Therefore, in this example, the lower number occurs when we number from left to right. The name of the parent chain in this example: octan - 4 - ol



Step 4: Identify and name the substituents (side chains). The substituents (side chains) acquire the position or number of the carbon atom to which they are attached.



In this example there are two methyl side chains on carbon 2 and 4.

Step 5: The name of the compound is composed of the name of the parent chain preceded by the names of the substituents in alphabetical order. The correct IUPAC name for the example is 2,4-dimethyloctan-4-ol.

Remember: In IUPAC nomenclature, a hyphen (-) separates numbers from words and a comma (,) separates numbers from numbers. There is no space between the words that make up the name. Marks will be lost if the hyphen or comma is omitted.

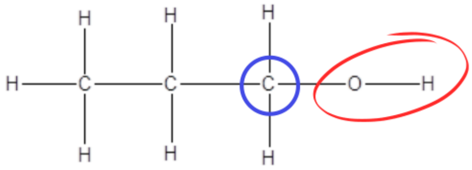
NOTE:

- It is possible for the organic molecule (alcohol) to have more than one hydroxyl group:
- The presence of two –OH groups is indicated by –**di**ol in the IUPAC name.
- Three -OH groups is indicated by–**tri**ol in the IUPAC name.

Primary, secondary and tertiary haloalkanes

1. Primary alcohols

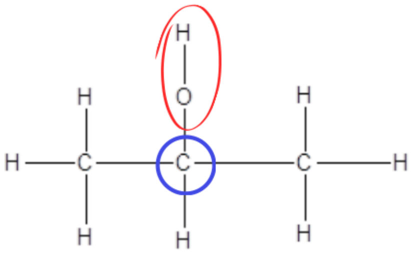
Example: propan - 1 - ol



In primary (1°) alcohols, the carbon to which the hydroxyl group (-OH) is bonded, is bonded to **ONE** other carbon atom.

2. Secondary alcohols

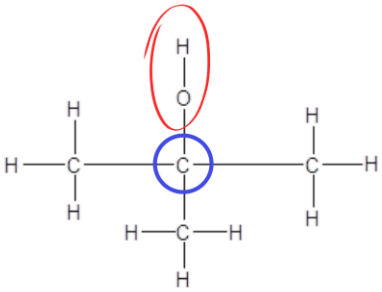
Example: propan - 2 - ol



In secondary (2°) alcohols, the carbon to which the hydroxyl group (-OH) is bonded, is bonded to **TWO** other carbon atoms.

3. Tertiary alcohols

Example: 2 - methylpropan - 2 - ol



In tertiary (3°) alcohols, the carbon to which the hydroxyl group (-OH) is bonded, is bonded to **THREE** other carbon atoms.

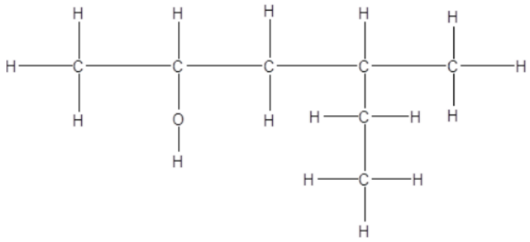
Worked example

Multiple choice question

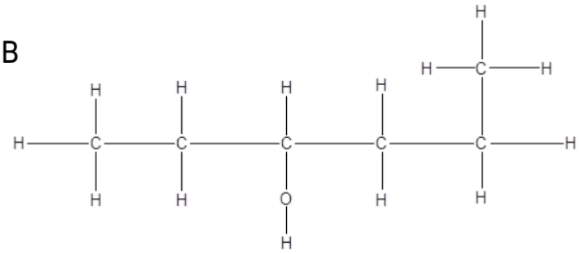
C + A

1. Which ONE of the following organic molecules represents the structural formula of 4 - methylhexan-3-ol:

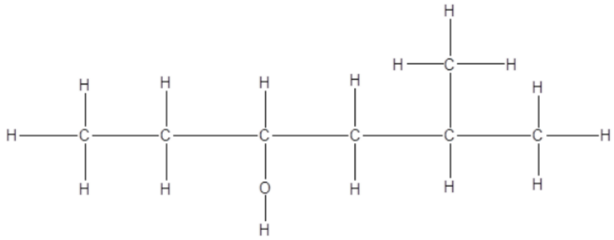
A



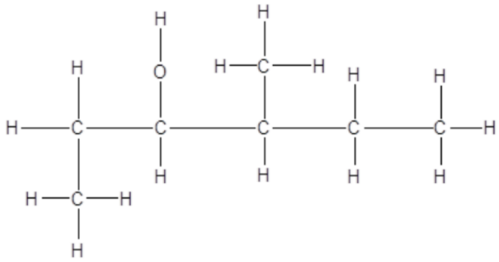
B



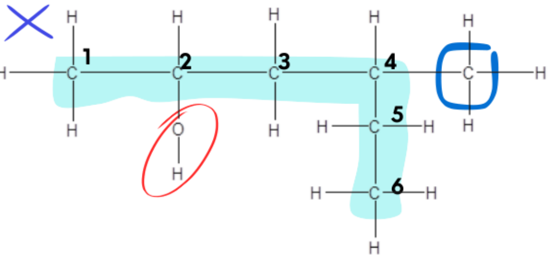
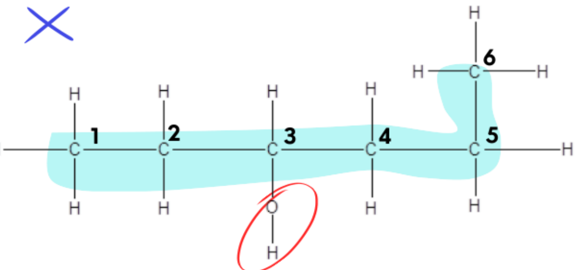
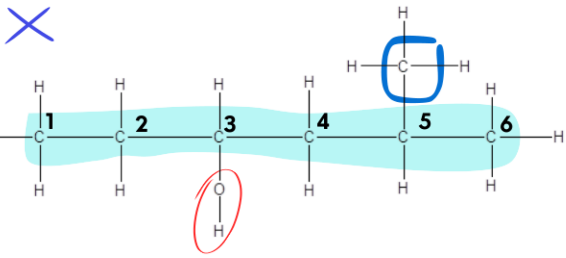
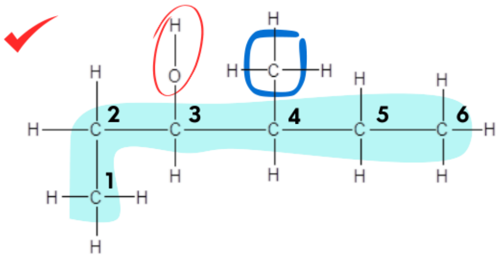
C



D

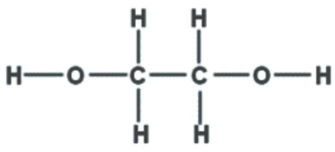
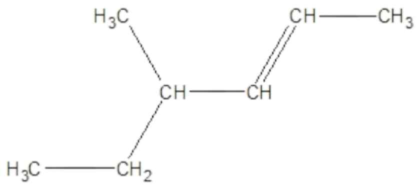


Answer: D

A  IUPAC name: 4-methylhexan-2-ol	B  IUPAC name: hexan-3-ol
C  IUPAC name: 5-methylhexan-3-ol	D  IUPAC name: 4-methylhexan-3-ol

Worked example

1. Organic molecules **A** - **D** are represented below.

A	B
$CH_3CHOHCH_3$	C_3H_8
C	D
	

1.1 Which of the organic molecules (**A - D**) represents:

1.1.1 an alcohol with ONE hydroxyl group. (1)

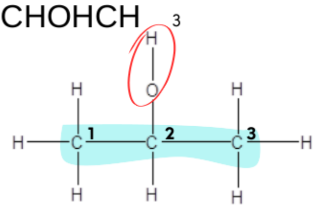
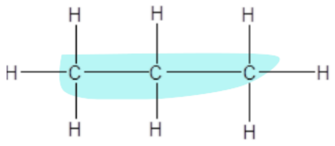
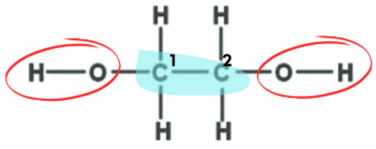
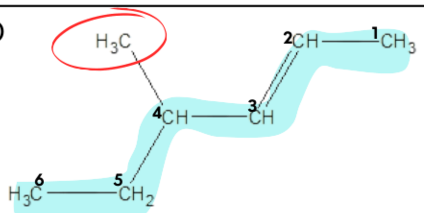
1.1.2 an organic molecule with the general formula C_nH_{2n+2} (1)

1.1.3 an unsaturated hydrocarbon. (1)

1.2 Write down the IUPAC name of organic molecule **C.** (2)

1.3 Write down the condensed structural formula of organic molecule **D.** (2)

1.1 Analyse and identify molecules **A - D** before answering the questions.

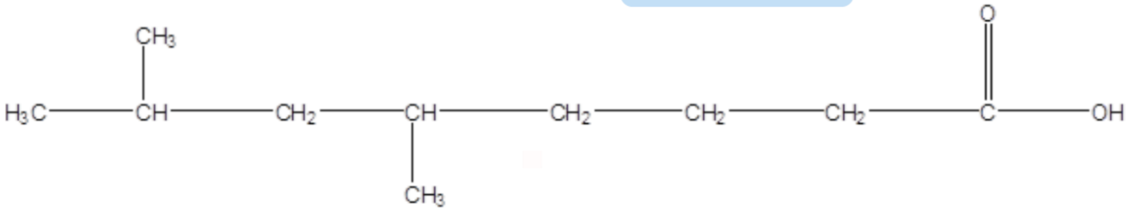
A	B
$CH_3CHOHCH_3$  **Homologous series:** alcohol **IUPAC name:** propan - 2- ol	C_3H_8  **Homologous series:** alkane **IUPAC name:** propane
C  **Homologous series:** alcohol **IUPAC name:** ethan-1,2-diol	D  **Homologous series:** alkene **IUPAC name:** 4-methylhex-2-ene

Note: This is an alcohol with **TWO** hydroxyl functional groups, therefore diol- is used.

Naming branched chained carboxylic acids

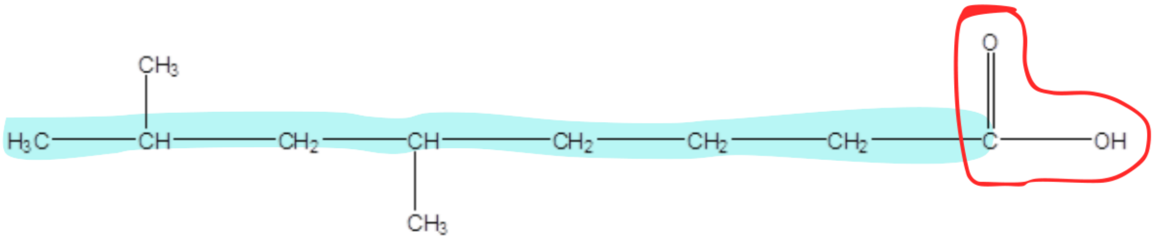
Example

Note: There are only single bonds between the carbon atoms in carboxylic acid molecules.

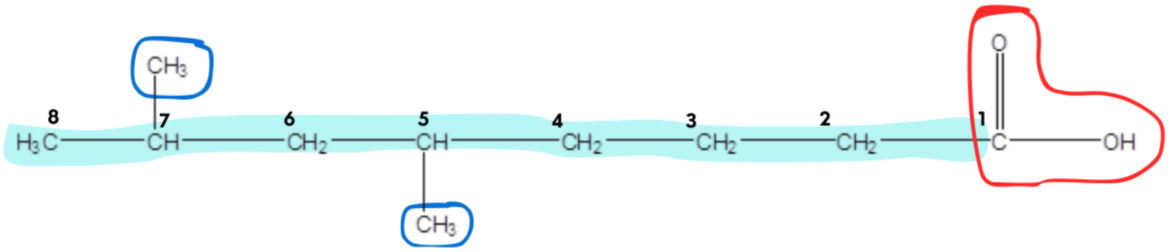


Step 1: Identify the carboxyl group (-COOH). The molecule is therefore a carboxylic acid.

Step 2: Select the longest continuous chain containing the – COOH (carboxyl) group. This is the parent chain. In this example, the parent chain has eight carbon atoms. To name the parent chain, change the ending "e" in the alkane to "oic acid". The name of the parent chain is **octanoic acid**.



Step 3: Number the parent chain, starting at the carbon containing the carboxyl group. This is allocated the number 1. The carbon containing the carboxyl group is always allocated position 1 and its position is not indicted in the IUPAC name because its position does not change.



Step 4: Identify the substituents (side chains). They are then assigned the number of the carbon to which they are attached. In the example the substituents are called the 5- methyl group and the 7- methyl group. Since there are TWO methyl side chains, the prefix di- is used to indicate this i.e., 5,7 - dimethyl.

Step 4: The name of the compound is now composed of the side chains, in alphabetical order, followed by the name of the parent chain. The correct IUPAC name for the example is 5, 7-dimethyloctanoic acid.

1.1.1 A

Molecule **A** is propan-2- ol which only has ONE hydroxyl group.

1.1.2 B

Molecule **B** is an alkane, therefore, it has the general formula C_nH_{2n+2}

1.1.3 D

Molecule **D** is an alkene, therefore, it is an unsaturated compound (hydrocarbon)

1.2 ethan-1,2-diol

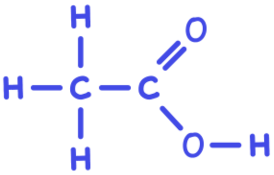
Note: This is an alcohol with TWO hydroxyl functional groups, therefore diol- is used.

1.3 $CH_3CHCHCH(CH_3)CH_2CH_3$

NOTE: How to write the condensed structural formula

- When writing the condensed structural formula, start at carbon **1,** and follow through with summarising the number of hydrogen atoms bonded to carbon 2, 3 etc
- The side chains (or substituents) are represented in brackets in the condensed structural formula - note CH_3 = methyl CH_2CH_3 = ethyl
- If the carbon chain repeats, this can be represented in brackets, with a subscript representing the carbon chain repeating.

Carboxylic acids

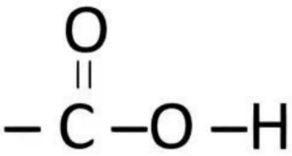


Carboxylic acids are a homologous series of organic compounds that have acid properties. They are weak acids. An example of a well-known carboxylic acid is ethanoic acid found in vinegar.

Functional group of carboxylic acids

Carboxylic acids are characterised by both –OH and =O attached to the same carbon atom.

Structural formula of functional group of carboxylic acids:



$$-\overset{\overset{\Large O}{||}}{C}-O-H$$

Remember: Every carbon must have four bonds.

Condensed structural formula for the functional group of carboxylic acids: **- COOH**

Name of the functional group of carboxylic acids:

Carboxyl group

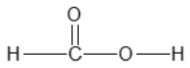
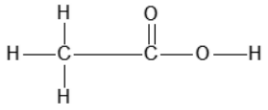
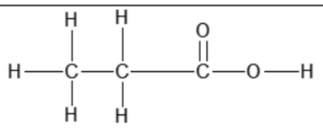
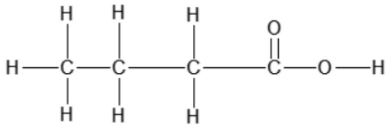
NOTE: The functional group occurs at the start of the carbon chain. Therefore, the carbon atom containing the functional group [carboxyl group (-COOH)] is always position 1 in the carbon chain.

PRO-TIPS

The name of the functional group of a carboxylic acid (carboxyl group) is in the name **carboxylic** acid.

Examples of carboxylic acids

The table below represents the IUPAC name, structural formula and molecular formula of the simplest carboxylic acids.

IUPAC name	Structural formula	Molecular formula
Methanoic acid		HCOOH
Ethanoic acid		CH_3COOH
Propanoic acid		C_2H_5COOH
Butanoic acid		C_3H_7COOH

PRO-TIPS

The position of the functional group (carboxyl group) in a carboxylic acid is not indicated in the IUPAC name because it is always carbon 1 and its position cannot change.

General formula for carboxylic acids:

$$\underbrace{C_nH_{2n+1}}\underbrace{COOH}$$

All the other carbon atoms in the molecule excluding the carboxyl group

Carbon atom containing the **carboxyl group**

Naming carboxylic acids: IUPAC nomenclature of carboxylic acids

Naming straight chained carboxylic acids

Step 1: Identify the carboxyl group (-COOH). The molecule is therefore a carboxylic acid.

Step 2: Count the number of carbon atoms to determine the longest parent chain containing the –COOH (carboxyl group)

Step 3: Replace the ending "e" in the corresponding alkane with **"oic acid."**

Note: There are only single bonds between the carbon atoms in carboxylic acid molecules.

Worked example

1. Consider the two organic molecules, **P** and **Q**, shown below:

P 2 - methylpentanoic acid **Q** $C_3H_6O_2$

1.1 Write down the structural formula of the homologous series to which both organic molecule **P** and **Q** belong. (2)

1.2 For molecule **P**, write down the:

1.2.1 structural formula (2)

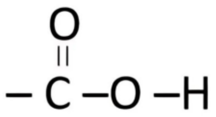
1.2.2 IUPAC name of the straight -chained carboxylic acid, with the same molecular formula as organic molecule **P**. (2)

1.3 Which organic molecule has the empirical formula $C_3H_6O_2$?

Write down **P** only or **Q** only or both **P** and **Q**. (2)

1.1 Organic molecule **P** is a carboxylic acid and organic molecule **Q** is a carboxylic acid. Although the molecular formula of organic molecule **Q** is not in the conventional form, it can be written in the conventional form: C_3H_5COOH, therefore it is propanoic acid.

Structural formula of the functional group of a carboxylic acid:

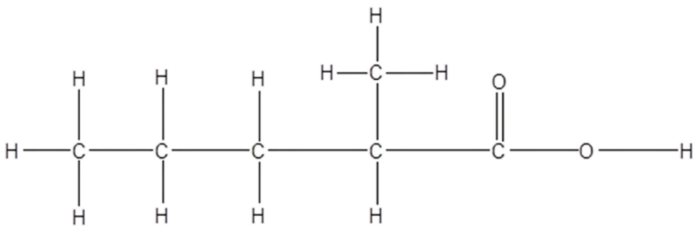


$$-\overset{\overset{\text{O}}{\|}}{\text{C}}-\text{O}-\text{H}$$

1.2.1 When writing the structural formula, start by drawing the parent chain with the carboxyl functional group as carbon 1, followed by the side chains in the correct positions, in this question, the methyl side chain is on carbon 2.

Remember:

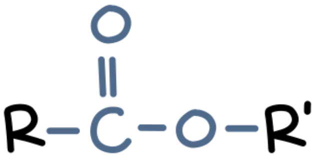
- Show all bond lines
- Check that every carbon has formed four bonds.



1.2.2 A straight - chained carboxylic acid of molecule **P** will have 6 carbon atoms in the parent chain. Therefore, the molecules IUPAC name is:
Hexanoic acid.

1.3 Molecular formula of molecule **P**: $C_6H_{12}O_2$
By dividing the number of moles of each atom by 2, this can be simplified to C_3H_6O.
Molecular formula of molecule **Q**: $C_3H_6O_2$. This cannot be simplified any further, therefore it is also the empirical formula of molecule **Q**.
Therefore, **Q** only.

Esters



$R-\overset{O}{\overset{\|}{C}}-O-R'$

An ester is an organic molecule that produces a pleasant, characteristic smell. Esters occur naturally in fruits and flowers, and are responsible for their pleasant smells.

How is an ester formed?

A ester is formed when an **alcohol** reacts with a **carboxylic acid** in the presence of a few drops of **concentrated** sulphuric acid (H_2SO_4) and mild heat.

Functions of the concentrated sulphuric acid:

1. To act as a catalyst (i.e., to speed up the rate of the chemical reaction).
2. To act as dehydrating agent

NOTE:
In grade 12, only primary alcohols will be used to produce esters. Alcohols are flammable.

Esterification

The type of reaction that takes place when a alcohol reacts with a carboxylic acid in the presence of a few drops of concentrated sulphuric acid and mild heat is called **esterification.**
The products produced in a esterification reaction are:
1. an ester (organic product)
2. water (inorganic product)

Chemical equation in words to represent esterification:

$$\textbf{Alcohol + carboxylic acid} \xrightarrow{\text{Conc. } H_2SO_4} \textbf{ester + water}$$

PRO-TIPS
When **drawing** the structural formula of the alcohol and the carboxylic acid used to form the ester, draw the structures with the hydroxyl groups facing each other (**inwards**)

Uses of esters

- Fragrances and perfumes
- Flavours (food flavouring)
- Used as solvents
- Esters are used as monomers for poly**ester**

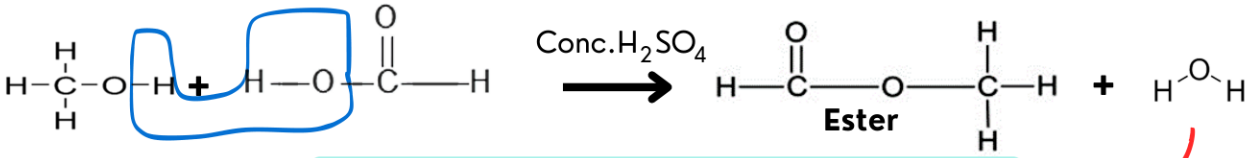
Example

1. Methanol and methanoic acid are heated in the presence of a few drops of concentrated sulphuric acid.

1.1 Write down a balanced chemical equation using the structural formula. (4)

NOTE: The concentrated H_2SO_4 must be indicated above the arrow in an esterification reaction:

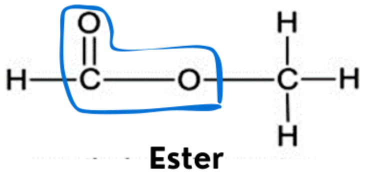
1.1



The water produced in an esterification reaction (H_2O)
- The -OH (hydroxyl group) is derived from the carboxylic acid
- the - H (H atom) is dervied from the alcohol

Functional group of an ester

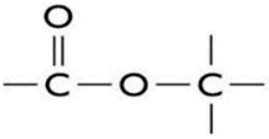
From the example,



Ester

Esters are characterised by a carbon chain interrupted by an oxygen atom, with the adjacent carbon containing a double bond with another oxygen atom (= O)

Structure of the functional group of an ester:



Remember: Every carbon must have four bonds.

Condensed structural formula of the functional group of an ester:

-COO-

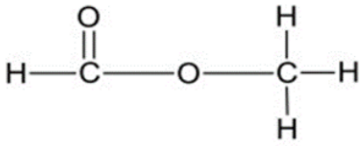
General formula for esters

$C_nH_{2n}O_2$

This is the same general formula as carboxylic acids

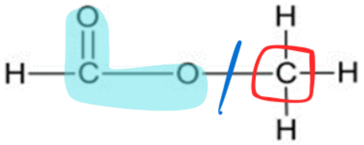
IUPAC nomenclature: Naming esters

From the example:



Step 1: To name an ester from the structural formula, find the oxygen atom that interrupts the carbon chain and divide the chain into two parts:

1. The parent chain, which consists of BOTH oxygen atoms.
2. The side chain or substituent (which contains only carbon and hydrogen atoms, no oxygen atoms).



Parent chain **Side chain**

↓ ↓

Derived from the straight chained carboxylic acid that reacted

Derived from the primary alcohol that reacted

Step 2: Naming the side chain or substituent (derived from the primary alcohol):

The alkyl group (side chain or substituent) is named first and it is named according to the number of carbon and hydrogen atoms in side chain.

Methyl ($-CH_3$), Ethyl ($-C_2H_5$), Propyl ($-C_3H_7$) etc.

Step 3: Naming the parent chain (derived from the straight - chained carboxylic acid)

The parent chain consists of both oxygen atoms, and is derived from the carboxylic acid that reacted.The suffix "oic acid" in the IUPAC name of the carboxylic acid is changed to "oate" (due to the presence of oxygen atoms)

From the example, methanoic acid was used therefore the IUPAC name of the parent chain of the ester: meth**an**oate

'an' indicates single bonds between the carbon atoms.

IUPAC name of the ester from the example: methyl methanoate

Methanol and methanoic acid did react (in the presence of concentrated sulphuric acid) to form this ester

NOTE: The name of the ester is usually written as two **separate words,** with a space between the alkyl group (side chain) and the name of the parent chain.

Worked example

Multiple choice questions

1. Consider the organic compound propyl butanoate, an ester which produces a pineapple odour. Which ONE of the following represents the alcohol and carboxylic acid that reacted to produce the ester?

	Alcohol	carboxylic acid
A	butan - 1 - ol	propanoic acid
B	propan-1-ol	butanoic acid
C	propan - 2 -ol	butanoic acid
D	propan - 1 - ol	2 - methylpropanoic acid

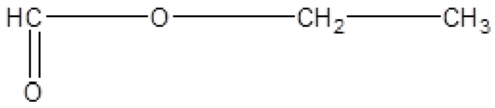
PRO-TIPS

IUPAC naming of alcohols
If the position of the hydroxyl group can change, its position must be included in the IUPAC name of the alcohol. Position 1 is used, where necessary, to indicate that it is a **primary** alcohol.

Answer: B

In the organic compound, propyl butanoate, propyl is the side chain (substituent) which is derived from the **primary** alcohol that reacted, which is propan - 1 - ol.
The parent chain, butanoate, is derived from the straight- chained carboxylic acid that reacted. In this reaction, butanoic acid is the carboxylic acid that reacted.

2. An organic molecule is represented below:



$$\underset{\underset{O}{\|}}{HC}-O-CH_2-CH_3$$

Which ONE of the following represents the IUPAC name and the molecular formula of the organic molecule?

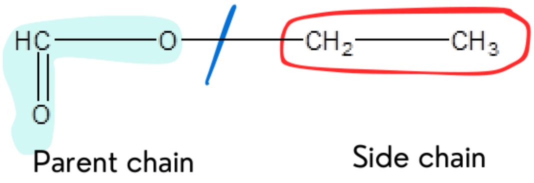
	IUPAC name	Molecular formula
A	ethyl methanoate	$C_2H_6O_2$
B	propanoate	$C_3H_6O_2$
C	methyl ethanoate	$C_3H_6O_2$
D	ethyl methanoate	$C_3H_6O_2$

Answer: D

This organic molecule is an ester because the carbon chain is interrupted by an oxygen atom and the adjacent carbon has a double bond with another oxygen atom.

To determine the IUPAC name of the ester:

1. Find the carbon atom that interrupts the carbon chain and divide the chain into two parts. Remember that the parent chain consists of both oxygen atoms and the side chain ONLY consists of carbon and hydrogen atoms.



Conclusions:

- The side chain was derived from the alcohol, in this example, ethanol and is therefore an **ethyl side chain.**
- The parent chain was derived from the carboxylic acid, in this example, methanoic acid and is therefore **methanoate**.

IUPAC name: ethyl methanoate

Molecular formula: This can be determined using the general formula for esters: $C_nH_{2n}O_2$

OR

The number of carbon, hydrogen and oxygen atoms in the organic molecule can be counted.

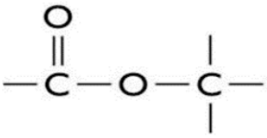
$C_3H_6O_2$

Worked example

1. Given the organic molecule: pentyl ethanoate.
   Write down:
   1.1 The homologous series to which this compound belongs. (1)
   1.2 The structural formula of the functional group of ethyl ethanoate. (2)
   1.3 The name of the TWO organic substances required to prepare this substance. (2)
   1.4 The structural formula of the substance. (2)

1.1 From the IUPAC name, it can be determined that this organic molecule is an ester.
Homologous series: Esters

1.2 Structural formula of the functional group of an ester:

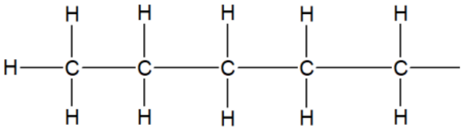


1.3 The two organic substances required to produce this ester is a primary alcohol and a straight -chained carboxylic acid.
From the IUPAC name:

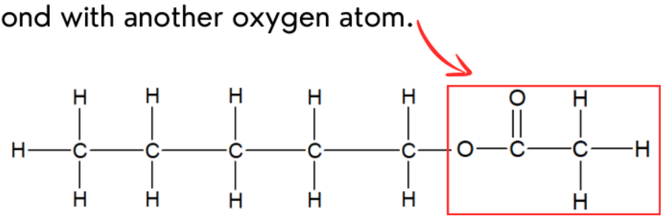
- **pentyl** (side chain) is derived from the primary alcohol, therefore the alcohol is pentan - 1 - ol. The position of the functional group must be indicated.
- **ethanoate** (the parent chain) is derived from the carboxylic acid, therefore the carboxylic acid that reacted is ethanoic acid.

Two organic reactants: pentan - 1 - ol and ethanoic acid

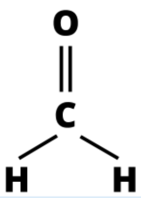
1.4 To draw the structural formula of an ester, start by drawing the side chain.
The pentyl side chain has 5 carbon atoms:



Now draw the parent chain after the side chain, starting with the oxygen atom that interrupts the carbon chain, and the adjacent carbon atom having a double bond with another oxygen atom.



Aldehydes



Functional group of an aldehyde

Aldehydes consist of a carbonyl group ($C = O$) with at least one hydrogen (H) atom attached to the same carbon (C) atom.

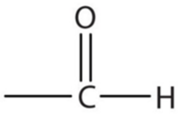
NOTE: In aldehydes, the functional group is always on carbon 1 in the parent chain, therefore its position is not indicated.

Name of the functional group of an aldehyde

Formyl group

DID YOU KNOW? Formyl is where the simplest aldehyde gets is more common name, formaldehyde.

Structural formula of the functional group



$$-\overset{\overset{\large O}{\|}}{C}-H$$

Condensed structural formula of the functional group

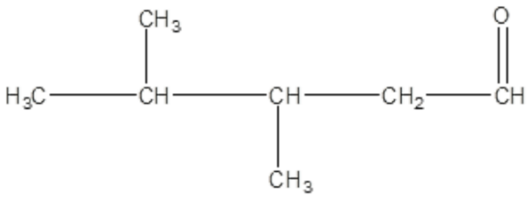
$$-CHO$$

General formula of aldehydes:

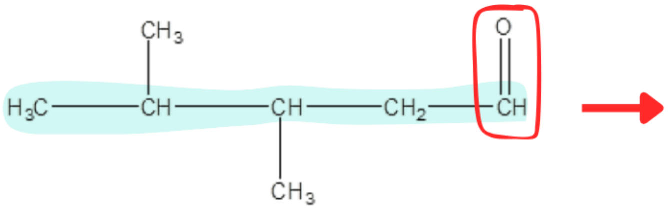
$$C_nH_{2n}O$$

IUPAC nomenclature: naming aldehydes

Example:



Step 1: Identify the longest, continuous carbon chain, containing the carbonyl group (C=O) group.

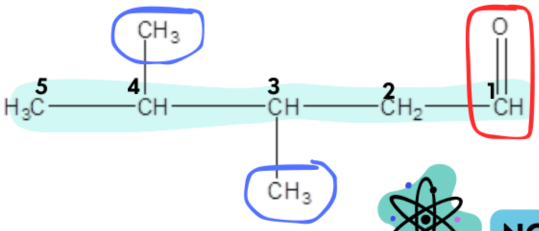


Aldehyde functional group

Naming the parent chain: Identify the number of carbon atoms in the parent chain. The parent chain ends in the suffix **-al** to indicate that it is a aldehyde. In the example, there are 5 carbon atoms in the parent chain, therefore the name of the parent chain is **pentanal.**

'an' indicates single bonds between the carbon atoms.

Step 2: Identify the the side chains or substituents. Number the parent chain, starting from the carbon atom containing the functional group (-CHO), this is taken as carbon 1 (position 1). Identify the positions of the side chains.
The side chains must be arranged in alphabetical order and the position of the side chain must be indicated.



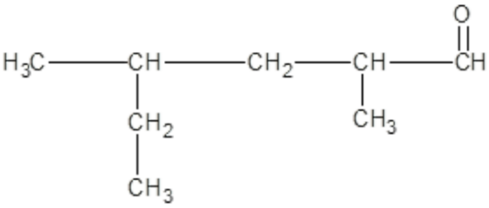
IUPAC name: 3,4 - dimethylpentanal

NOTE: The functional group always occurs at the start of the carbon chain, therefore, the carbon atom containing the functional group is **carbon 1** (taken as position 1).

Worked example

Multiple choice questions

1. An organic molecule is represented below:

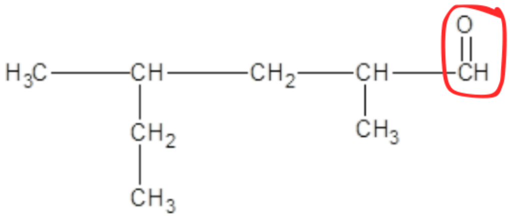


Which ONE of the following represents the IUPAC name and the condensed structural formula of the functional group of the organic molecule?

	IUPAC name	Condensed structural formula of functional group
A	4-ethyl-3-methylpentanal	-CHO
B	2,4-dimethylhexanal	-CHO
C	2,4-methylhexan-1-al	-CHO
D	2,4-dimethylhexanol	-CO

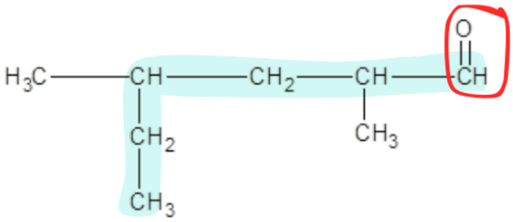
Answer: B

The organic molecule is an aldehyde and the functional group (-CHO) occurs at the start of the chain:

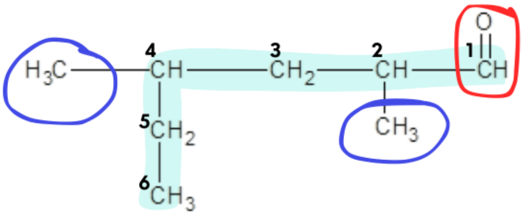


To name the organic molecule:

Identify the longest, continuous chain, this is the parent chain. In this example, the parent chain has six carbon atoms, and is therefore hexanal. The position of the functional group is not indicated.

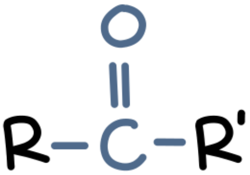


Identify the side chains (substituents) and number the parent chain, starting at the functional group. The functional group is given position 1.



IUPAC name: 2,4 -dimethylhexanal

Ketones



$$R-\overset{O}{\overset{\|}{C}}-R'$$

Functional group of a ketone

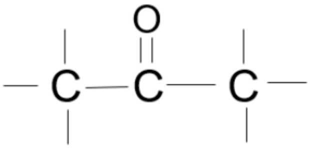
Ketones are characterised by a carbonyl group (C=O) and where the carbon (C) atom of the carbonyl group is attached to two other carbon (C) atoms.

NOTE: There are no hydrogen atoms bonded to the carbonyl group, like in an aldehyde.

Name of the functional group of a ketone

Carbonyl group (C = O)

Structural formula of the functional group



Condensed structural formula of the functional group

$>CO$

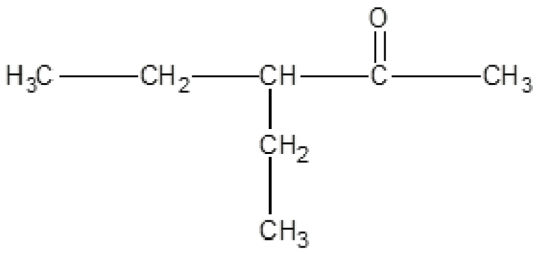
General formula of ketones:

$C_nH_{2n}O$

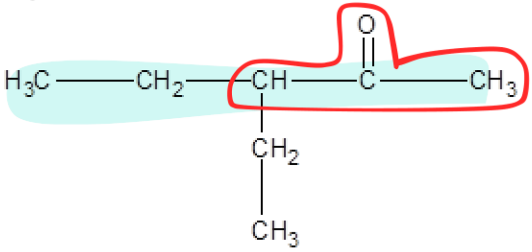
Same general formula as aldehydes

IUPAC nomenclature: naming ketones

Example:

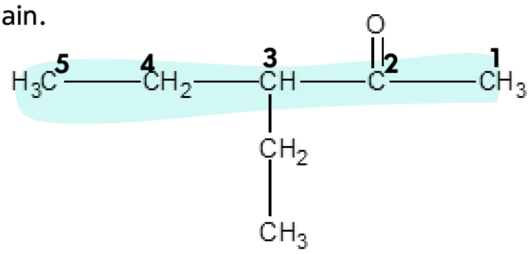


Step 1: Identify the longest, continuous carbon chain, containing the carbonyl group (C=O) group. **Note:** the carbonyl group has two other carbon atoms bonded to it, therefore the organic molecule is a ketone.



Naming the parent chain:

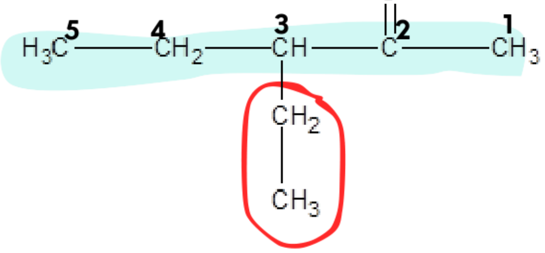
Step 2: Number the parent chain, such that the functional group (carbonyl group, C = O) ends up on the lower position. In this example, this is from right to left. Identify the number of carbon atoms in the parent chain.



The parent chain ends in the suffix **-one** to indicate that it is a ketone. In the example, there are 5 carbon atoms in the parent chain, therefore the name of the parent chain is **pent<u>an</u> - 2-one.**

'an' indicates single bonds between the carbon atoms.

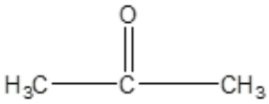
Step 3: Identify the side chains or substituents and identify the positions of the side chains. The side chains must be arranged in alphabetical order and the position of the side chain must be indicated. In this example, the side chain is an ethyl side chain on carbon 3.



IUPAC name: 3 - ethylpentan-2-one

Worked example

1. Three organic molecules **A**, **B and C** are represented below.

A	$CH_3COC(CH_3)_2CH_2CH_3$
B	5-ethyl-4-methyl-heptanal
C	 $H_3C-\overset{\overset{O}{\|\|}}{C}-CH_3$

1.1 Identify which of the organic molecules (**A** - **C**) represents a ketone? (2)

1.2 Write down the molecular formula of organic molecule **B**. (2)

1.3 Write down the IUPAC name of organic molecule **C**. (2)

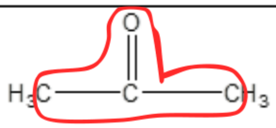
1.4 Consider organic molecule **A**.

1.4.1 Write down the structural formula of organic molecule **A.** (2)

1.4.2 Write down the name of the functional group of organic molecule **A**. (1)

1.4.3 Write down the IUPAC name of organic molecule **A**. (2)

1.1

A	$CH_3\boxed{CO}C(CH_3)_2CH_2CH_3$	→ **Ketone**
B	5-ethyl-4-methyl-heptanal	→ **Aldehyde**
C	 $H_3C-\overset{\overset{O}{\|\|}}{C}-CH_3$	→ **Ketone**

∴ A and C

1.2 Organic molecule **B** is an aldehyde therefore it has the general formula: $C_nH_{2n}O$

Therefore are 10 carbon atoms in organic molecule B:

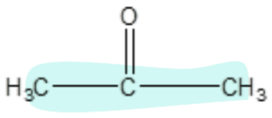
ethyl = 2 carbon atoms

methyl = 1 carbon atom

heptanal = 7 carbon atoms

∴ $C_{10}H_{20}O$

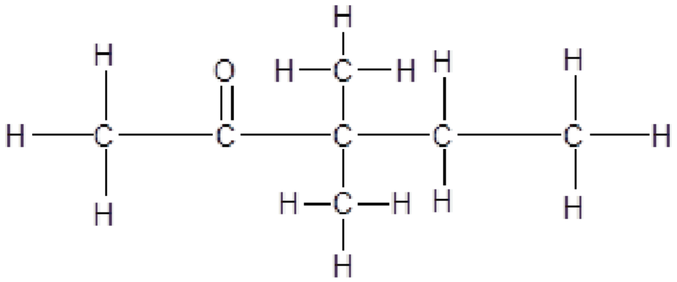
1.3 Organic molecule **B** has a carbonyl group (C = O),therefore it is a ketone. There are three carbon atoms in the parent chain. The position of the functional group (carbonyl group (C=O) cannot change in this organic molecule, therefore, its position is not indicated in the IUPAC name:



IUPAC name: propanone

DID YOU KNOW? Propanone is the simplest ketone.

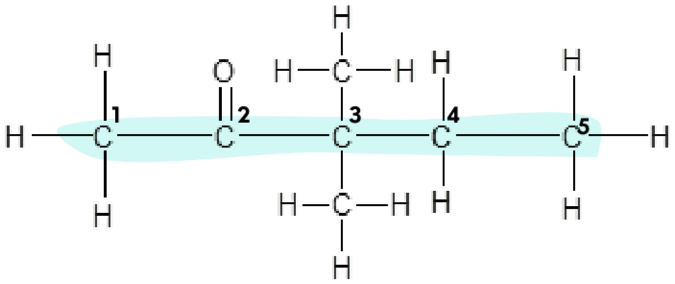
1.4.1 When drawing the structural formula from the condensed structural formula, start at carbon 1 and follow through. Always check that every carbon has 4 bonds.



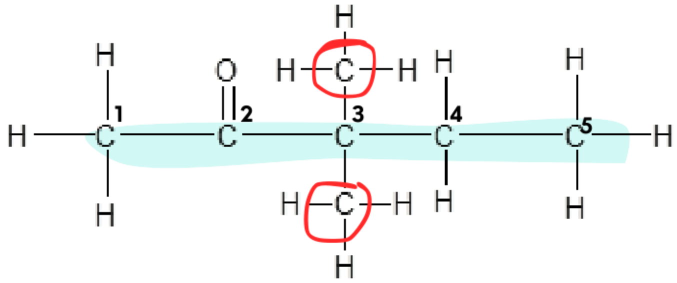
1.4.2 Organic molecule **A** is a ketone.

The functional group is called the **carbonyl group.**

1.4.3 When naming a ketone, identify the longest, continuous chain containing the functional group (carbonyl group C = O). Number the parent chain such that the functional group ends up on the lower position. In this example, the parent chain has 5 carbon atoms and is therefore pentan - 2 - one. The position of the functional group can change and therefore must be indicated.



Identify the side chains (substituents) and identify the positions of the side chains. The side chains are two methyl side chains, both on carbon 3.



IUPAC name: 3,3 - dimethylpentan - 2 - one

Structural isomerism

In nature, it is possible for organic compounds can have the **same molecular formula but different structures**. These molecules are **structural isomers** of each other.

Definition: Structural isomers: Organic molecules with the same molecular formula, but different structural formulae.

NOTE: Structural isomers is a general term to describe organic molecules with the **same** molecular **formula** but **different structural** formulae.

There are three different types of structural isomers covered in grade 12:

1. Chain isomers
2. Positional isomers
3. Functional isomers (covered later in this chapter)

1. Chain isomers

There are two different types of chains that organic molecules can structurally have. This affects the physical properties of the organic molecules.

Straight chain or bent chain (results in the organic molecule having a greater surface area)
Branched chain (decreases the surface area of the organic molecule)

What are chain isomers?

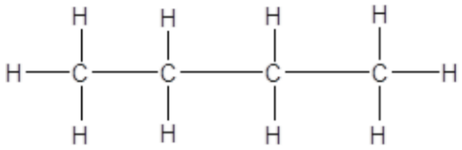
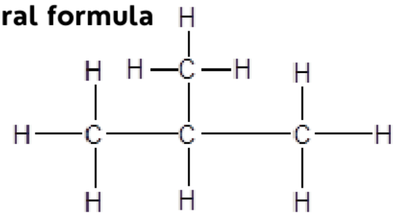
Definition: **Chain isomers:** Organic molecules with the same molecular formula, but different types of chains.

PRO-TIPS

Chain isomers belong to the same **homologous** series and have the same molecular formula. The **only** difference is the type of chain:

- One molecule has a **straight** chain (or bent chain) and the other a **branched** chain.

Example of chain isomers

Butane	**2 - methylpropane**
Homologous series Alkane	**Homologous series** Alkane
Structural formula  **Type of chain:** Butane has a straight chain	**Structural formula**  **Type of chain:** 2 - methylpropane has a branched chain
Molecular formula C_4H_{10}	**Molecular formula** C_4H_{10}

Butane and 2-methylpropane are chain isomers. Butane has a straight chain, where as 2 – methylpropane has a branched chain. While their structure is different, their molecular formula is the same.

2. Positional isomers

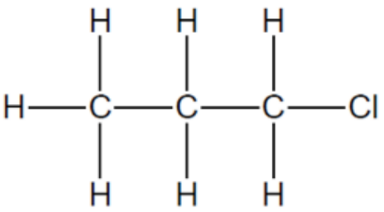
Organic molecules that belong to the same homologous series with the SAME type of chain and have the same molecular formula, can have side chains or substituents or functional groups on **different positions** on the parent chain. These molecules are positional isomers of eachother.

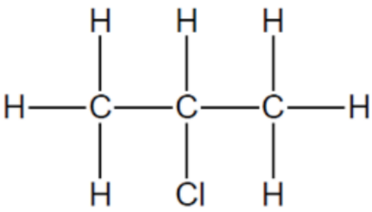
What are positional isomers?

Definition: Positional isomers: Organic molecules with the same molecular formula, but different positions of the side chain, substituents or functional groups on the parent chain.

Examples of positional isomers

1 - chloropropane **and** **2 - chloropropane**





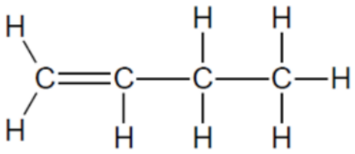
Both 1 - choropropane and 2 - chloropropane:

- are **haloalkanes and have the same halogen (same functional group)**
- Have the **same molecular formula (C_3H_7Cl)**
- Have the **same type of chain**

The **only** difference between the two organic molecules is the position of the halogen side chain (or functional group). Therefore, they are positional isomers of each other.

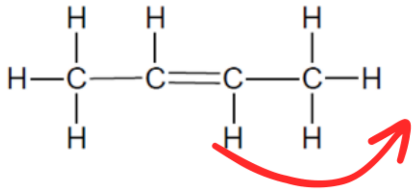
Other examples of positional isomers:

But - 1 - ene



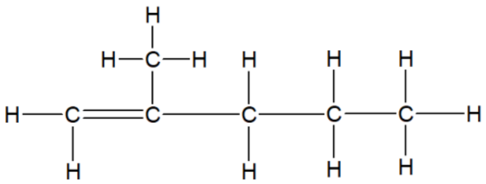
and

But - 2 - ene



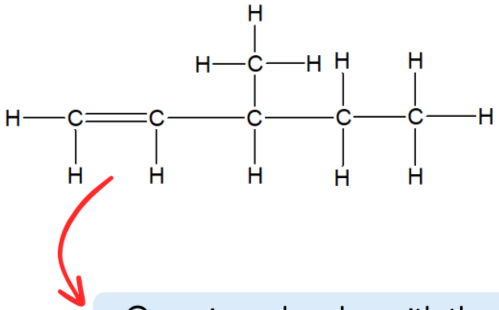
- Organic molecules with the same functional group (i.e. from the same homologous series [alkenes]) with the same molecular formula and type of chain.
- Only the position of the functional group (the double bond) has changed.

2 - methylpent-1-ene



and

3 - methylpent-1-ene



- Organic molecules with the same functional group (i.e., from the same homologous series [alkenes]) with the same molecular formula and type of chain.
- Only the position of the methyl side chain has changed but the position of the functional group has stayed the same.

3. Functional isomers

Organic molecules can have the same molecular formula and the same type of chain, but have **different functional groups** (therefore the organic molecules belong to different homologous series). These organic molecules are functional isomers of each other.

What are functional isomers?

Definition: Functional isomers: Organic molecules with the same molecular formula, but different functional groups.

Examples of functional isomers

1. **Esters and carboxylic acids** have the same molecular formula $C_nH_{2n}O_2$
2. **Aldehydes and ketones** have the same molecular formula $C_nH_{2n}O$

Examples of carboxylic acid and ester functional isomers

Organic molecules and functional isomers		Molecular formula of isomers
Butanoic acid ↔	Methyl propanoate Ethyl ethanoate Propyl methanoate	$C_4H_8O_2$
Pentanoic acid ↔	Methyl butanoate Ethyl propanoate Propyl ethanoate Butyl methanoate	$C_5H_{10}O_2$

Examples of aldehyde and ketone functional isomers

Organic molecules and functional isomers		Molecular formula of isomers
propanal ↔	propanone	C_3H_6O
butanal ↔	butan – 2 – one	C_4H_8O
pentanal ↔	pentan – 2 – one or pentan – 3 – one	$C_5H_{10}O$

Worked example

Multiple choice questions

1. Which ONE of the following represents a chain isomer of pentane?

A 2 - ethylpropane

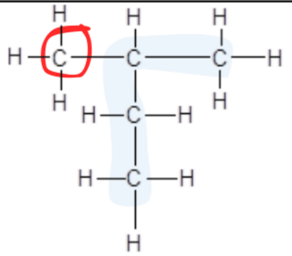
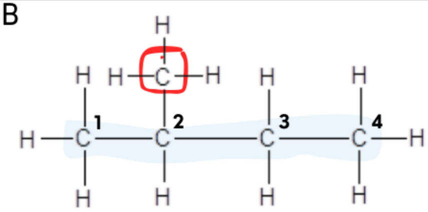
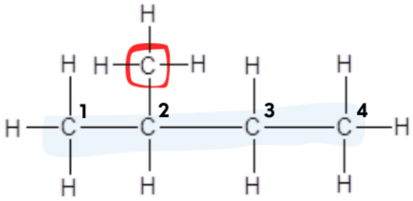
B 2 - methylbutane

C pent - 1 - ene

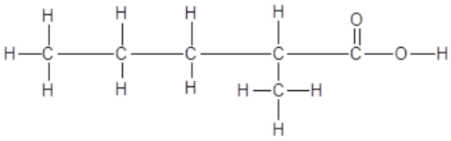
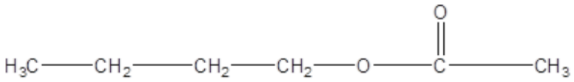
D 3 - methylbutane

Answer: B

Pentane is a straight chained alkane. Therefore, a chain isomer of pentane must be a **branched chain alkane**. Check each of the structural formulae of these organic molecules to determine which organic molecule is a branched chained alkane with the correct structural formula.

A  ✗ 2- ethylpropane is not structurally possible or correct.	B  ✓ 2- methylbutane is structurally possible or correct and therefore 2 - methylbutane, due to it having a branched chain, is a chain isomer of pentane
C ✗ Pent-1-ene is an alkene and therefore belongs to a different homologous series and has a different molecular formula than pentane. Pent-1-ene and pentane are not isomers of each other.	D  ✗ 3- methylbutane is not the correct IUPAC name for this organic molecule, therefore, while is is a brached chained alkane, it is not correctly name according to IUPAC nomenclature.

2. Four organic compounds **A - D** are represented below.

A 	B  $H_3C-CH_2-CH_2-CH_2-O-C(=O)-CH_3$
C ethyl propanoate	D 3 - methylpentanoic acid

Which ONE of the following compounds is a functional isomer of hexanoic acid?

A compound **A**

B compound **B**

C compound **C**

D compound **D**

Answer: B

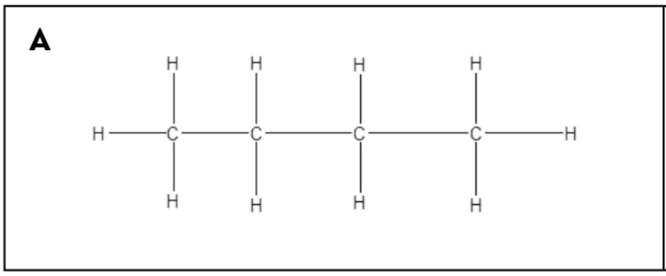
Hexanoic acid is a carboxylic acid, therefore, a functional isomer of a carboxylic acid, is an ester. In order for an ester to be a functional isomer, it must have the same molecular formula as hexanoic acid ($C_6H_{12}O_2$).

✗ Compound **A** is a carboxylic acid and a **chain isomer** of hexanoic acid.
✓ Compound **B** is an ester with the molecular formula $C_6H_{12}O_2$. This is a functional isomer of hexanoic acid.
✗ Compound **C** is an ester, but it has a molecular formula $C_5H_{10}O_2$. This does not match the molecular formula of hexanoic acid, and therefore it is not a functional isomer of hexanoic acid.
✗ Compound **D** is a carboxylic acid and a **chain isomer** of hexanoic acid.

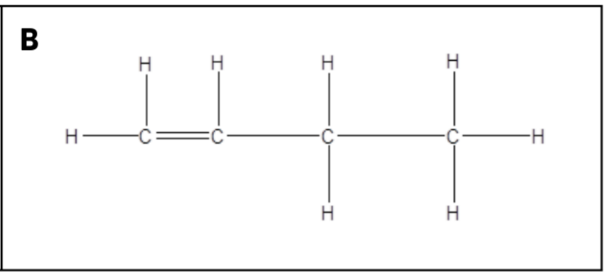
Worked example

1. Organic molecules **A** and **B** are represented below.

A



B



1.1 Define the term chain isomers (2)

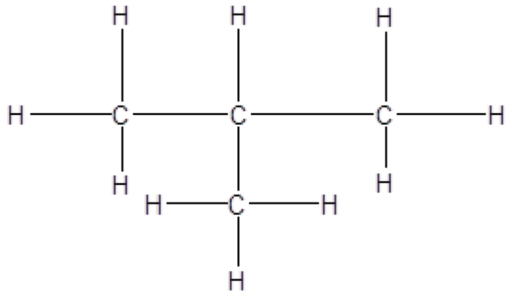
1.2 Write down the structural formula of a chain isomer of organic molecule **A**. (2)

1.3 Write down the IUPAC name of a positional isomer of compound **B**. (2)

1.4 Which ONE of the above compounds is an unsaturated compound? Explain the answer. (2)

1.1 Organic molecules with the same molecular formula but different types of chains.

1.2 Organic molecule **A** is a straight chained alkane. Therefore a chain isomer of organic molecule **A** has a branched chain. One of the carbon atoms at the end can be repositioned to form a methyl side chain on carbon 2.

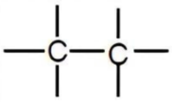
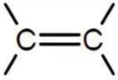
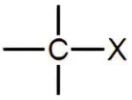
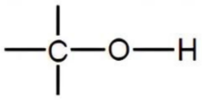
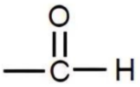
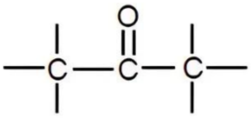
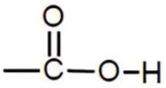
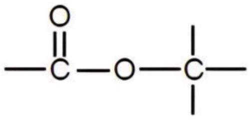


Remember that chain isomers must have the same molecular formula

1.3 Molecule **B** is an alkene, therefore, a positional isomer of molecule **B** will have the functional group (the double bond) in a different position, namely between carbon 2 and carbon 3.
∴ But - 2 - ene

1.4 Compound **B**.
Compound **B** has a double bond between the carbon atoms, therefore it is an unsaturated compound.

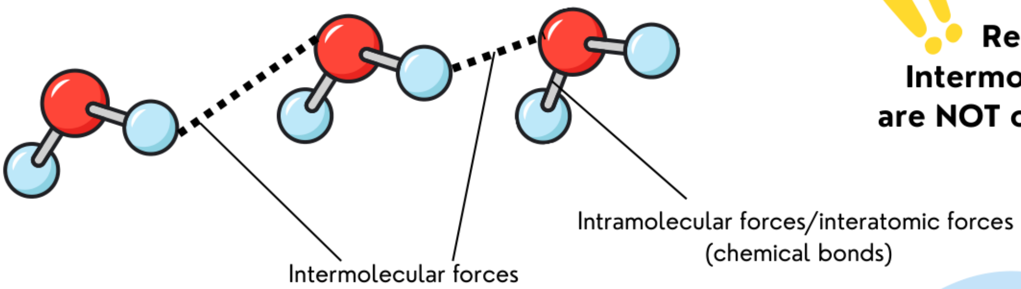
Summary of the organic molecules covered in this section:

Homologous series	Structure of functional group	
	Structure	**Name/Description**
Alkanes	 $-\overset{\mid}{\underset{\mid}{C}}-\overset{\mid}{\underset{\mid}{C}}-$	Only C-H and C-C single bonds
Alkenes	 $>C=C<$	Carbon-carbon double bond
Alkynes	$-C\equiv C-$	Carbon-carbon triple bond
Haloalkanes	 $-\overset{\mid}{\underset{\mid}{C}}-X$ (X = F, Cℓ, Br, I)	Halogen atom bonded to a saturated C atom
alcohols	 $-\overset{\mid}{\underset{\mid}{C}}-O-H$	Hydroxyl group bonded to a saturated C atom
Aldehydes	 $-\overset{O}{\overset{\|}{C}}-H$	Formyl group
Ketones	 $-\overset{\mid}{\underset{\mid}{C}}-\overset{O}{\overset{\|}{C}}-\overset{\mid}{\underset{\mid}{C}}-$	Carbonyl group bonded to two C atoms
Carboxylic acids	 $-\overset{O}{\overset{\|}{C}}-O-H$	Carboxyl group
Esters	 $-\overset{O}{\overset{\|}{C}}-O-\overset{\mid}{\underset{\mid}{C}}-$	-

ORGANIC CHEMISTRY: PART 2
INTERMOLECULAR FORCES AND THE EFFECT ON PHYSICAL PROPERTIES

Intermolecular forces

Intermolecular forces are forces of attraction between the molecules.
Intermolecular forces hold the molecules together, but they are weaker than chemical bonds or int**ra**molecular forces.



Remember: Intermolecular forces are NOT chemical bonds.

Types of intermolecular forces

Van der Waals forces:

Van der Waals forces are weaker intermolecular forces which includes London forces and dipole - dipole forces.

1. **London forces** (induced dipole - induced dipole forces/ dispersion forces)
   London forces occur between NON- POLAR molecules, where there is an even distribution of charge across the molecule.

PRO-TIPS

London forces were named after the German Physicist Fritz London. While there are many variations to the name, it is most commonly called London Forces.

How do these intermolecular forces occur if there are no permanent dipoles?

- Due to the electrons being constantly in motion, sometimes there are more electrons on one end. Resulting in that end of the molecule being partially negative and the other end partially positive, this **INDUCES** a dipole in the molecule, resulting in a temporary/momentary dipole.
- This temporary/ momentary dipole induces a dipole in a neighbouring molecule, resulting in more temporary/ momentary dipoles being induced, and therefore a force of attraction between the molecules occur.
- This explains why London forces are also called induced dipole – induced dipole forces/ dispersion forces/ momentary forces.

Strength of London forces

London forces are the **weakest** type of intermolecular forces.

Which organic molecules have London forces between their molecules?

- **All** organic molecules have London forces between the molecules.

Between the following molecules **only** London forces occur:

- Alkanes
- Alkenes
- Alkynes

Non - polar molecules

2. Dipole - dipoles forces

- Dipole- dipole forces occur between **polar molecules** that have an uneven distribution of charge and permanent dipoles (except polar molecules containing H bonded to F,O, N as this is a special type of dipole- dipole force, namely hydrogen bonding).
- Dipole - dipole forces occurs between the partially positive end of the one molecule and the partially negative end of the other molecule.

Strength of dipole - dipole forces

Dipole - dipole forces are stronger than London forces, but weaker than hydrogen bonds/hydrogen bonding.

Which organic molecules have dipole - dipole forces between their molecules?

- Carboxylic acids
- Haloalkanes
- Esters
- Aldehydes
- Ketones

Polar molecules

3. Hydrogen bonding

- When hydrogen (H) bonds to fluorine (F) or oxygen (O) or nitrogen (N), a polar molecule with a large dipole moment is formed. This is because F, O and N have high electronegativities.
- A hydrogen bond occurs between the H atom of the one molecule, and the N or O or F atom on the other molecule.
- Hydrogen bonding is a very strong type of dipole - dipole force, because F, O and N have high electronegativities and due to the small atomic radius of H, F, O and N atoms, the molecules can therefore approach each other more closely and thus, the force of attraction between the molecules is greater than ordinary dipole interactions because it acts over a shorter distance.
- Hydrogen bonding is the **strongest type of intermolecular forces.**

Which organic molecules have hydrogen bonds between their molecules?

- Alcohols (1 site for hydrogen bonding)
- Carboxylic acids (2 sites for hydrogen bonding)

Polar molecules with H and O atoms

Remember: Hydrogen bonds are intermolecular forces <u>not</u> chemical bonds.

ONE site for hydrogen bonding between oxygen and hydrogen

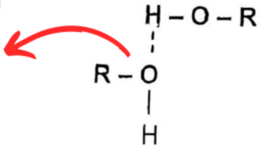


Figure 1: Alcohol with only ONE site for hydrogen bonding

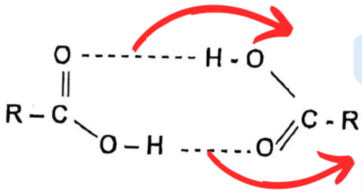


Figure 2: Carboxylic acid with TWO sites for hydrogen bonding

TWO sites for hydrogen bonding between oxygen and hydrogen

Physical properties and the effect of intermolecular forces on physical properties

There are **three** physical properties that will be studied in this section, and the effect that the strength of the intermolecular forces have on these physical properties:

1. Melting point
2. Boiling point
3. Vapour pressure

1. Melting point

Melting is a phase change from a solid to a liquid. When a substance melts, it absorbs energy to overcome the intermolecular forces between the molecules and therefore move the particles further apart.

Definition: **Melting point**: Temperature at which the solid and liquid phases of a substance are at equilibrium.

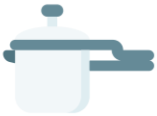
General **trend** in the strength of the intermolecular forces and the melting point of a substance:

- The **stronger intermolecular** forces between the molecules, the **more energy** is required to overcome the intermolecular forces between the molecules.
- The **higher** the **melting** point of the substance.

OR

- The **weaker** the **intermolecular** forces between the molecules, the **less energy** is required to overcome the intermolecular forces between the molecules.
- The **lower** the **melting** point of the substance.

2. Vapour pressure



Definition: Vapour pressure: Pressure exerted by a vapour at equilibrium with its liquid in a closed system.

PRO-TIPS

A closed system is a term only used in **chemistry**.
A closed system is a system that is isolated from its surroundings.
It is able to exchange energy with its surroundings but not matter.

When a substance (i.e., a liquid) is heated in a sealed container (closed system), some of the molecules evaporate and collide with the sides of the container, resulting in a pressure above the substance's surface. This is called the vapour pressure.

NOTE:

- The vapour pressure of a substance at any given temperature is an indication of the strength of the intermolecular forces between its particles in the liquid or solid phase.
- For simplicity and understanding, vapour pressure of a substance can be used to measure the ability for a substance to change phase into a gas.
- Liquids particles change phase to gas particles more readily at higher temperatures, therefore vapour pressure of a substance increases with increasing temperature.

General trend in the strength of the intermolecular forces and the vapour pressure of a substance

- It can be concluded that **the higher the vapour pressure of a substance** (at any given temperature), the weaker the intermolecular forces between the particles and the less energy is required to overcome the intermolecular forces between the particles.

OR

- The lower the vapour pressure of a substance (at any given temperature), the stronger the intermolecular forces between the particles and the more energy is required to overcome the intermolecular forces between the particles

3. Boiling point

Boiling is the phase change from a liquid to a gas. There is a link between the boiling point of a substance and its vapour pressure.

Definition: **Boiling point**: The temperature at which the vapour pressure of a substance equals the atmospheric pressure.

In figure 3 below, the temperature at which the pressure within the closed system is equal to the external atmospheric pressure, is the boiling point of the substance. Water has a boiling point of approximately 100°C at sea level, where the air pressure is approximately 1 atmosphere (1 atm).

Graph of temperature vs vapour pressure for water

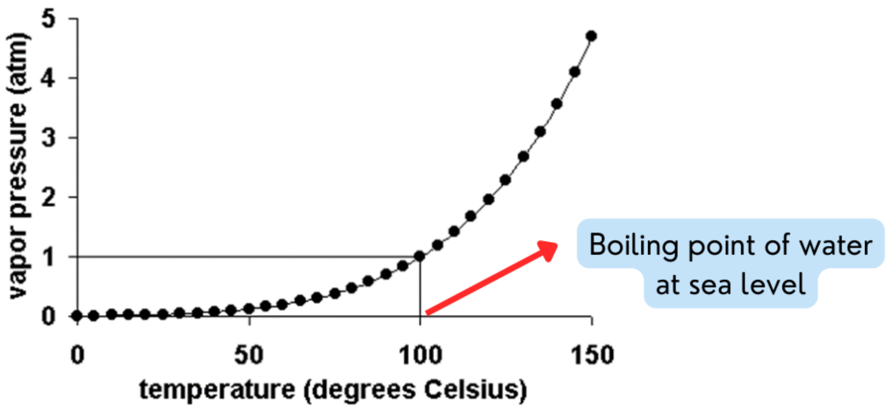


Figure 3: Temperature versus vapour pressure graph, for water.

NOTE: There is a relationship between the boiling point of a substance and its vapour pressure:

- The higher the boiling point of a substance, the lower the vapour pressure.
- The lower the boiling point of a substance, the higher the vapour pressure.

General trend in the strength of the intermolecular forces and the boiling point of a substance:

- The **stronger** intermolecular forces between the molecules, the **more energy** is required to overcome the intermolecular forces between the molecules.
- The **higher** the **boiling** point of the substance.

OR

- The **weaker** the intermolecular forces between the molecules, the **less energy** is required to overcome the intermolecular forces between the molecules.
- The **lower** the **boiling** point of the substance.

The relationship between the structure and physical properties (boiling point, melting point, vapour pressure) of organic molecules

The strength of the intermolecular forces between the molecules affects the physical properties (i.e., the melting point, boiling point and vapour pressure) of a substance.

Factors such as:

1. **M**olecular mass (i.e. chain length or number of carbon atoms in the carbon chain)
2. **S**urface area (i.e. straight chain vs branched chains)
3. **T**ype of Functional group
4. **N**umber of functional groups

...affects the strength of the intermolecular forces between the substance, and therefore the physical properties (melting point, boiling point and vapour pressure) of the substance.

In this section it will be investigated how these factors affect the melting point, boiling point and vapour pressure of a substance.

1. The effect of molecular mass (chain length) on the melting point, boiling point and vapour pressure of a substance

- The **greater** the molecular mass of substance, the **greater** the **surface** area over which the intermolecular forces interact.

↓

- The **stronger** the **intermolecular** forces between the molecules.

↓

- The **more energy** is required to overcome the intermolecular forces between the molecules

↓

- The **higher** the melting and boiling point, and the **lower** the vapour pressure of the substance.

OR

- The **smaller** the molecular mass of substance, the **smaller** the **surface** area over which the intermolecular forces interact.

↓

- The **weaker** the **intermolecular** forces between the molecules.

↓

- The **less energy** is required to overcome the intermolecular forces between the molecules

↓

- The **lower** the melting and boiling point, and the **higher** the vapour pressure of the substance.

NOTE: When the molecular mass of different substances are compared to determine the effect that it has on the melting point, boiling point and vapour pressure of a substance; in order for the investigation to be a fair test, all the other factors that affect the strength of the intermolecular forces i.e., the type of functional group, the number of functional groups and the surface area (type of chain) must be kept constant.

Worked example

C + A

1. An investigation is conducted to determine how molecular mass affects the boiling points of five organic compounds.

COMPOUND	BOILING POINT
Methane	-162°C
Ethane	-89 °C
Propane	-42 °C
Butane	-1°C
Pentane	36°C

1.1 For this investigation, write down:

1.1.1 The independent variable (1)

1.1.2 The dependent variable (1)

1.1.3 A controlled variable (1)

1.1.4 A conclusion (2)

1.2 Which of these organic compounds will have the lowest vapour pressure? Use the information in the table to explain the answer. (2)

1.3 Explain why butane has a higher boiling point than ethane. (3)

1.1.1 The independent variable is the variable that is deliberately changed or manipulated in the investigation. In this investigation the number of carbon and hydrogen atoms is being changed, therefore changing the molecular mass or chain length.
∴ Molecular mass or chain length or number of **carbon and hydrogen** atoms

1.1.2 The dependent variable is the variable being measured.
In this investigation, the boiling point is being measured.

1.1.3 The control variable is the variable that is being kept constant in this investigation. It is all the other factors that can affect the strength of the intermolecular forces. Control variables ensure that the investigation is a fair test i.e., that it only has one independent variable.

∴Homologous series (alkanes) or type of functional group or type of chain (straight chain).

1.1.4 A conclusion must include the relationship between the independent and dependent variable. As the molecular mass or chain length (of straight chained alkanes) increases, the boiling point increases.

1.2 There is a relationship between the vapour pressure of a substance and its boiling point. The higher the boiling point of a substance, the stronger the intermolecular forces between the molecules, the lower the vapour pressure.

Pentane. Pentane has the highest boiling point, therefore it has the lowest vapour pressure.

PRO-TIPS

If the question asks for information to be taken from the **table**, a link must be made to the question and the **information/variables** in the table. In this question, it can be explained why pentane has the **lowest vapour** pressure by linking it to the fact that it has the highest boiling point, and will therefore not turn into a gas very easily (i.e., at lower temperatures)

1.3 When explaining why one substance has a higher/lower boiling point/melting point/vapour pressure than the other, **compare** the:

- Type of intermolecular forces between the various molecules.
- factor affecting the strength of the intermolecular forces.
- strength of the intermolecular forces between the molecules
- energy required to overcome the intermolecular forces between the molecules.
- effect on the physical propertie/s.

- Butane and ethane are alkanes, therefore the type of intermolecular forces between their molecules is London forces only.
- However, butane has a greater molecular mass/ chain length than ethane.
- Therefore, there are stronger intermolecular forces between the butane molecules **than** the ethane molecules.
- More energy is required to overcome the intermolecular forces between the butane molecules **than** ethane molecules.
- Therefore the butane will have a higher boiling point **than** ethane.

PRO-TIPS

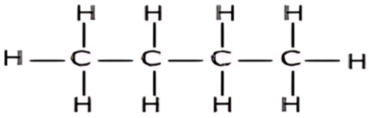
- When writing an explanation on why the substances have different meting and boiling point, always do a **comparison.**
- Use bullet points when writing explanations - this makes it easier for the marker to read.
- **Do not refer to the intermolecular forces as bonds.** Only intermolecular forces are overcome when a phase change takes place.

2. The effect of surface area on the melting point, boiling point and vapour pressure of a substance

- **Increasing** the number of **branches** (i.e., increasing the degree of branching) **decreases** the **surface area** of the molecule. The greater the number of branches, the smaller the surface area over which the intermolecular forces can interact.
- Therefore, the **weaker** the **intermolecular** forces between the molecules.
- **Less energy** is required to overcome the intermolecular forces between the molecules.
- Therefore, the **lower** the **melting** and **boiling point**, and the higher the vapour pressure of the molecule.

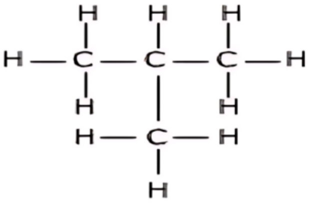
Example

Butane
(straight chained)
Melting point: -138°C
Boiling point: 0,5°C



VS

2 – methylpropane
(chain isomer of butane: branched chain)
Melting point: - 159,6°C



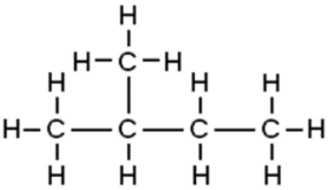
- **Straight** chained organic molecule (more linear molecule).
- **Greater** surface **area** over which the intermolecular forces can interact.
- **Stronger intermolecular** forces between the molecules.
- **Higher melting** and **boiling** point compared to isomers with branched chains (e.g., 2 -methylpropane)
- **Lower vapour pressure** compared to isomers with branched chains (e.g., 2 -methylpropane)

- 2- methylpropane is a **chain** isomer of butane and has a **branched** chain.
- **Smaller** surface area than butane due to the branch (resulting in the molecule being more compact).
- **Lower melting** and **boiling** point compared to isomers with straight chains (e.g., butane).
- **Higher vapour** pressure compared to isomers with straight chains (e.g., butane).

The effect of symmetry on the melting point

As the number of branches increases and the molecule becomes more symmetrical and more spherical, the melting point increases because the molecules are able to be more tightly packed in the solid phase, resulting in stronger intermolecular forces between the molecules. **Symmetry increases the melting point.**

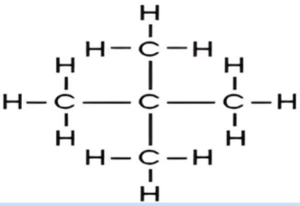
2 – methylbutane
Melting point: -159,77°C



VS

Higher melting point compared to 2 - methylbutane

2,2 – dimethylpropane
Melting point: -16,5°C

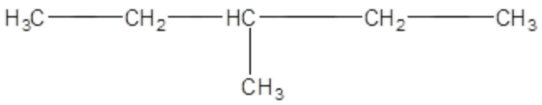
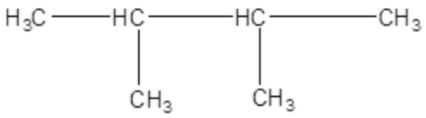


2,2 - dimethylpropane is more symmetrical and spherical than 2 - methylbutane

Worked example

A + P

In an investigation to compare the boiling points of straight and branched chain alkanes (**A** - **C**) with the same number of carbon atoms, results were obtained and recorded in the table below.

Compound	**Structure**
A	$H_3C-CH_2-CH_2-CH_2-CH_2-CH_3$
B	 $H_3C-CH_2-\underset{CH_3}{\underset{\vert}{HC}}-CH_2-CH_3$
C	 $H_3C-\underset{CH_3}{\underset{\vert}{HC}}-\underset{CH_3}{\underset{\vert}{HC}}-CH_3$

1.1 For this investigation, write down:

1.1.1 the independent variable. (1)

1.1.2 the dependent variable. (1)

1.1.3 the control variable. (1)

1.2 The boiling points of the substances (**A - C**) are listed below, in no particular order:

63,3°C ; 58°C ; 68,7°C

1.2.1 Which one of the listed boiling points represents the boiling point of compound **C**? Explain the answer. (4)

1.2.2 Which compound (**A** - **C**) will have the lowest vapour pressure? Explain the answer. (4)

1.1.1 The independent variable is the variable being deliberately changed or manipulated in this investigation. In this investigation, compound **A** is a straight chained alkane, therefore it has a greater surface area compared to compound **B** and **C**, which both have branched chains. Compound **C** has a smaller surface area than compound **B**, as it has two branches, whereas compound **B** only has one branch.

∴ Surface area or degree of branching

1.1.2 The dependent variable is the variable being measured in this investigation. In this investigation the effect of surface area on the boiling point is being determined.

∴ Boiling point.

1.1.3 The control variable is the variable that is kept constant in this investigation. All the compounds, **A - C** are alkanes (i.e., they belong to the same homologous series), and they have the same number of carbon and hydrogen atoms, therefore, they have the same molecular mass.

∴ Molecular mass or Homologous series (alkanes)

1.2.1 58°C.

- Compound **C** has the greatest degree of branching compared to compound **A** and **B**, therefore, it has the smallest surface area over which the intermolecular forces can interact.
- All the compounds have **London forces** between the molecules, however, the intermolecular forces between the molecules of compound **C** are the **weakest** (compared to the intermolecular forces between molecule **A** and **B**).
- The **least** amount of energy is required to overcome the intermolecular forces between the molecules of compound **C**.
- Therefore, compound C has the **lowest** boiling point.

NOTE:
Alkanes only have London forces between their molecules.

1.2.2
- Compound **A** has a straight chain, therefore, it has the greatest surface area over which the intermolecular forces can interact.
- All the compounds have **London forces** between the molecules, however, the intermolecular forces between the molecules of compound **A** are the **strongest** (compared to the intermolecular forces between molecule **B** and **C**).
- The **highest** amount of energy is required to overcome the intermolecular forces between the molecules of compound **A.**
- Therefore, compound **A** has the **highest** boiling point and therefore the **lowest** vapour pressure.

3. The effect of the type of functional group on the melting point, boiling point and vapour pressure of a substance

Types of intermolecular forces in order of increasing strength:

London forces (weakest)

↓

Dipole - dipole forces

↓

Hydrogen bonds or hydrogen bonding (strongest)

Summary of the types of intermolecular forces between the organic molecules

Homologous series (Type of organic molecule)	Type of intermolecular forces between the molecules	Strength of the intermolecular forces
Alkanes	London forces only	Very weak
Alkenes	London forces only	Very weak
Alkynes	London forces only	Very weak
Aldehydes	London forces Dipole - dipole forces	Fairly strong
Ketones	London forces Dipole - dipole forces	Fairly strong
Esters	London forces Dipole - dipole forces	Fairly strong
Haloalkanes	London forces Dipole - dipole forces	Stronger
Alcohols	London forces One site for hydrogen bonding	Very strong intermolecular forces due to one site for hydrogen bonding
Carboxylic acids	London forces Dipole - dipole forces Two sites for hydrogen bonding	Strongest intermolecular forces between the molecules due to dipole - dipole forces and two sites for hydrogen bonding

NOTE: When comparing the strength of the intermolecular forces between molecules of different functional groups (or homologous series), the following factors that affect the strength of the intermolecular forces between the molecules must be kept constant:

- Molecular mass (molecules with similar molecular mass must be compared)
- Type of chain and surface area
- Number of functional groups.

Worked example

C + A

1. Organic compounds (**A** and **B**) shown below are compared.

A C_2H_5OH
B HCOOH

1.1 Write down the IUPAC name of organic compound **A**. (2)

1.2 Explain why this comparison is a fair test. (1)

1.3 Which compound, **A** or **B**, has a LOWER vapour pressure? Give a reason for the answer. (4)

1.1 Compound A is an alcohol with two carbon atoms in the carbon chain.
$\therefore$ Ethanol.

NOTE: Ethanol should not be named as ethan-1-ol, because the position of the functional group **cannot** change if there are only two carbon atoms in the carbon chain.

1.2 Calculate the molar mass (molecular mass) of compound **A** and **B.**
Compound **A** and **B** have different functional groups, therefore, in order for the comparison to be a fair test, their molecular mass must be the same or similar:

Compound A (ethanol):
$M(C_2H_5OH) = 2(12) + 5(1) + 16 + 1$
$M(C_2H_5OH) = 46\ g.mol^{-1}$

Compound B (methanoic acid):
$M(HCOOH) = 1 + 12 + 2(16) + 1$
$M(HCOOH) = 46\ g.mol^{-1}$

Compound **A** (ethanol) and compound **B** (methanoic acid) have the same molecular mass (46 $g.mol^{-1}$). Both molecules also have the same type of chain and only one functional group.
Therefore, this investigation only has **one independent variable** (i.e., the type of functional group) and is therefore a fair test.

1.3 When explaining why one substance has a lower vapour pressure than the other, **compare** the:

- type of intermolecular forces between the various molecules.
- factor affecting the strength of the intermolecular forces.
- strength of the intermolecular forces between the molecules.
- energy required to overcome the intermolecular forces between the molecules.
- effect on the vapour pressure

Compound **B**.

- Compound **B** is a carboxylic acid and compound **A** is an alcohol with the same molecular mass.
- The type of intermolecular forces found in compound **B**(carboxylic acid) are: London forces, dipole - dipole forces and TWO SITES FOR HYDROGEN BONDING, whereas compound **A** (alcohol) has London forces and only ONE SITE FOR HYDROGEN BONDING.
- Compound **B** has stronger intermolecular forces between its molecules than compound **A**.
- Due to compound **B** having stronger intermolecular forces between the molecules, more energy will be required to overcome the intermolecular forces between compound **B** than compound **A.**
- Therefore, compound **B** will have a lower vapour pressure.

4. The effect of the number of functional groups on the melting point, boiling point and vapour pressure of a substance

Generally, increasing the number of functional groups increases the strength of the intermolecular forces between the molecules.

Alcohols

- Alcohols can have **more** than one **hydroxyl** (-OH) functional group: **diols** have **two** hydroxyl functional groups (-OH) and **triols** have **three** hydroxyl functional groups (-OH).
- **Increasing** the number of hydroxyl (-OH) **functional** groups in alcohols, **increases** the number of **sites** for **hydrogen** bonding, therefore, **increasing** the **strength** of the intermolecular forces between the alcohol molecules.

Haloalkanes

- **Increasing** the number of **halogen** atoms in a haloalkane, **increases** the number of **sites** for **dipole - dipole** forces, therefore, **increasing** the **strength** of the intermolecular forces between the haloalkane molecules.

Carboxylic acids

- Carboxylic acids can have **two** carboxyl groups (-COOH) on **either end** of the molecule.
- **Increasing** the number of **carboxyl** (- COOH) functional groups in carboxylic acids, **increases** the number of sites for **hydrogen** bonding and **dipole - dipole** forces, therefore, increasing the **strength** of the intermolecular forces between the carboxylic acid molecules.

Worked example

Haloalkanes play an important role in the chemical industry. The following investigations can be used to compare the boiling points of different haloalkanes with each other.

INVESTIGATION 1	
IUPAC NAME	**BOILING POINT (°C)**
chloromethane	-24,1
dichloromethane	40,1
trichloromethane	61,8
tetrachloromethane	76,6

INVESTIGATION 2	
IUPAC NAME	**BOILING POINT (°C)**
fluoromethane	-78,4
chloromethane	-24,1
bromomethane	3,6
iodomethane	42,4

1.1 Write down a conclusion for INVESTIGATION 1. Give a reason for this conclusion. (4)

1.2 Write down the independent variable in INVESTIGATION 1 and INVESTIGATION 2. (2)

1.3 Write down the variable that must be kept constant to obtain the results in INVESTIGATION 1. (1)

1.1 In investigation 1, the number of functional groups (chlorine atoms) is increased from molecule to molecule, this increases the boiling point.

Conclusion:

As the number of functional groups (chlorine atoms) in the haloalkane increases, the boiling point increases.

- As the number of functional groups (chlorine atoms) increases, the number of sites for stronger dipole - dipole forces increases.
- Therefore, the strength of the intermolecular forces between the molecules increases.
- More energy is required to overcome the intermolecular forces between the molecules.
- Therefore, the greater the number of functional groups (chlorine atoms) in the organic molecule, the higher the boiling point.

1.2 The independent variable is the variable being deliberately changed in each of the investigations.

- In investigation 1 the **number of functional groups (chlorine atoms)** is being changed.
- In investigation 2, the **type of halogen atom** is being changed.

1.3 The control variable is the variable that is kept constant to ensure that the investigation is a fair test.

∴The same type of halogen atom (i.e., chlorine atom) must be added to the molecule.

Identifying the state of matter of a substance at any given temperature

The state of a substance depends on whether the temperature of the substance (**T**) is lower than its melting point, higher than its boiling or between the melting and boiling point:

	T < melting point **(The given temperature is less than the melting point)**	**Melting point < T < boiling point** **(The given temperature is greater than the melting point but less than the boiling point)**	**T > boiling point** **(The given temperature is above the boiling point)**
State of matter:	Solid	Liquid	Gas

Worked example

C + A

Multiple choice question

1.1 Compound **A - D** is represented in the table below:

Name	Melting point (°C)	Boiling point (°C)
Compound **A**	-183	-162
Compound **B**	-182,8	-88
Compound **C**	-95	69
Compound **D**	-90.5	98

Which ONE of the following substances is a liquid a 25°C?

A Compound A, B and C.

B Compound C only.

C Compound D only.

D Compound C and D.

Answer: D

The given temperature, 25°C:

- ✗ Is above the boiling point of compound **A**, therefore, compound A is a gas at 25°C.
- ✗ Is above the boiling point of compound **B**, therefore, compound A is a gas at 25°C.
- ✓ Is greater than the melting point, but lower than the boiling point of compound **C**, therefore compound **C** is a liquid at 25°C .
- ✓ Is greater than the melting point, but lower than the boiling point of compound **D**, therefore compound **D** is a liquid at 25°C .

ORGANIC CHEMISTRY: PART 3

ORGANIC REACTIONS

1. Combustion reactions

All hydrocarbons, namely alkanes, alkenes and alkynes undergo combustion reactions, where they burn in the presence of oxygen, in a highly exothermic reaction ($\triangle H < 0$) that releases heat and light energy.

There are **two** types of combustion reactions:

1. Complete combustion
2. Incomplete combustion.

NOTE:
An exothermic reaction is a chemical reaction that **releases** energy.

Complete combustion of alkanes

Complete combustion takes place when an alkane burns in excess oxygen to produce carbon dioxide (CO_2), water and energy which is released in the form of heat and light.

General equation of the complete combustion of an alkane:

Alkane + oxygen ⟶ carbon dioxide + water + energy

NOTE:
Know how to **identify** and **write** balanced complete and incomplete combustion reactions.

Example:

Write the balanced equation for ethane burning in excess oxygen.
Excess oxygen means that the combustion reaction will be complete combustion.
To write a balanced complete combustion reaction:

1. Identify the chemical formulae of all reactants and products.

Reactants:
Ethane: C_2H_6
Oxygen: O_2

Remember that oxygen exists as a diatomic molecule in nature.

Products:
Carbon dioxide: CO_2 (produced in a complete combustion reaction)
Water: H_2O

2. Write the reaction using symbols, and a arrow to represent the change from reactants to products.

$$C_2H_6 + O_2 \rightarrow CO_2 + H_2O$$

3. Balance the reaction. Where possible, change the odd number of atoms to an even number of atoms.

$$2\,C_2H_6 + 7O_2 \rightarrow 4\,CO_2 + 6H_2O$$

Incomplete combustion of alkanes

Incomplete combustion takes place when an alkane or alkene or an alkyne burns in a **limited** amount of oxygen to produce carbon monoxide (CO) + water + energy.

General equation of the incomplete combustion of alkanes:

Alkane + oxygen → carbon monoxide (CO) + water + energy

2. Esterification reactions

In an esterification reaction, an **ester** is produced.

Remember that esters and esterification reactions were covered in organic chemistry part 1.

Reactants needed for an esterification reaction

An **alcohol** and a **carboxylic acid** react in the presence of a few drops of **concentrated sulphuric acid** (H_2SO_4) and **mild heat.** The reaction can be heated using a water bath, to ensure a more even distribution of heat, and because alcohols are flammable, they must not be placed in direct contact with the flame.

Function of the sulphuric acid

- Acts as a catalyst i.e., it increases the rate of the chemical reaction.
- Acts as a dehydrating agent, resulting in water being produced in the reaction.

Example:

Write a balanced equation for the following reaction:

$$\text{propan-1-ol + ethanoic acid} \xrightarrow{\text{Conc. } H_2SO_4} \text{propyl ethanoate + water}$$

Propyl ethanoate is an ester, with a general formula $C_nH_{2n}O_2$.

PRO-TIPS

When writing an esterification reaction, the reaction condition, concentrated H_2SO_4 ,**must** be written above the arrow.

To write a balanced esterification reaction:

1. Identify the chemical formulae of all reactants and products.

Reactants:

Propan - 1 - ol: C_3H_7OH

Ethanoic acid: CH_3COOH

Products:

Propyl ethanoate (ester with 5 carbon atoms in its carbon chain): $C_5H_{10}O_2$

Water: H_2O

Write the reaction using symbols, and a arrow to represent the change from reactants to products.

$$C_3H_7OH + CH_3COOH \xrightarrow{\text{Conc. } H_2SO_4} C_5H_{10}O_2 + H_2O$$ ✓ **Balanced**

Check that the reaction is balanced, where necessary, balance the reaction.

3. Substitution reactions

Substitution reactions occur when an atom (or group of atoms) is **replaced** by another (or a group of atoms).

Substitution reactions are undergone by **saturated compounds** namely:

- Alkanes
- Alcohols
- Haloalkanes.

Three types of substitution reactions:

1. Alkane to haloalkane (halogenation)
2. Haloalkane to alcohol (hydrolysis)
3. Alcohol to haloalkane

NOTE:
In a substitution reaction, a saturated compound is converted into another saturated compound.

3.1 Halogenation: Alkane reacts with a halogen to form a haloalkane

In a halogenation substitution reaction, one or more of the hydrogen atoms in the alkane molecule is substituted by a halogen atom. This process is called **halogenation**.

Reaction conditions for halogenation:

- Ultraviolet (UV) light **OR** sunlight
- Heat.

NOTE:
A halogenation reaction cannot take place without the presence of UV light and heat

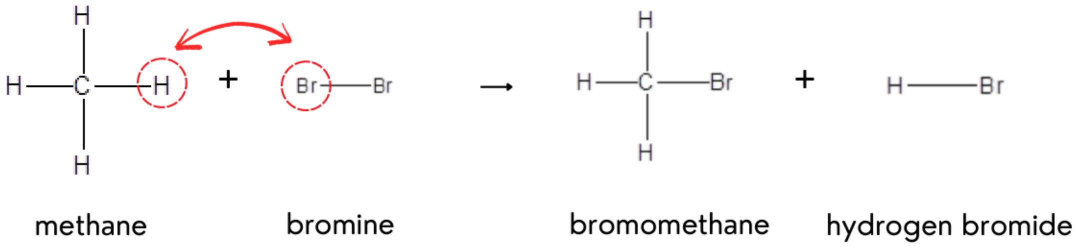
General equation for halogenation:

Alkane + X_2(X = Br, Cl, I, F) ⟶ **Haloalkane** (organic product) + **hydrogen halide** (by product)

Example

Methane reacts with bromine water in the presence of mild heat and UV light.

Balanced reaction using the structural formulae:



NOTE: During halogenation, a hydrogen atom in the alkane gets substituted (replaced) by a halogen atom

Balanced reaction using the molecular formulae:

$$CH_4 + Br_2 \longrightarrow CH_3Br + HBr$$

PRO-TIPS

List of **seven** elements that exist as diatomic molecules in nature:

Hydrogen (H_2)
Oxygen (O_2)
Nitrogen (N_2)
Fluorine (F_2)
Chlorine (Cl_2)
Bromine (Br_2)
Iodine (I_2)

Test for alkanes and alkenes using bromine water (test for saturation)

Bromine water is a reddish - brown solution of bromine. It is formed when the diatomic bromine (Br_2) is dissolved in water (H_2O).

Test for alkanes and alkenes

Alkanes are far less reactive than alkenes, therefore, alkanes will not react with bromine water unless UV light is present.

Results

Bromine water reacted with an alkene (halogenation - addition reaction covered later).
Bromine water reacts spontaneously with an alkene. The bromine water becomes **decolourised or brown colour disappears** when it reacts with an alkene**.** The bromine atoms react with the carbon atoms that form the double bond.

Bromine water reacted with an alkane
Bromine water does not react with an alkane and remains reddish brown in colour when reacted with an alkane.

Conclusion

- Alkenes can react with decolourise bromine water.
- Alkanes cannot react with bromine water, unless UV light is present because alkanes are far less reactive than alkenes.

3.2 Hydrolysis: haloalkane to alcohol using a dilute strong base or water

Hydrolysis (substitution) occurs when the halogen atom on the haloalkane is substituted by a hydroxyl group.
The hydroxyl group (-OH) can be supplied by either a dilute strong base or by excess water. These reactions are thus called hydrolysis reactions.

In a hydrolysis reaction, a haloalkane is converted into an alcohol (hydrolysis) using:

- a dilute strong base e.g., dilute NaOH/ KOH/ LiOH

OR

- water

Hydrolysis using a dilute strong base

The haloalkane is dissolved in ethanol before being treated with an aqueous **dilute** strong base
[e.g. NaOH (aq)] and mild warming of the mixture.

Reaction conditions:

1. A dilute strong base must be used (NaOH/ KOH/ LiOH)
2. Mild heat
3. Dissolve the haloalkane in ethanol.

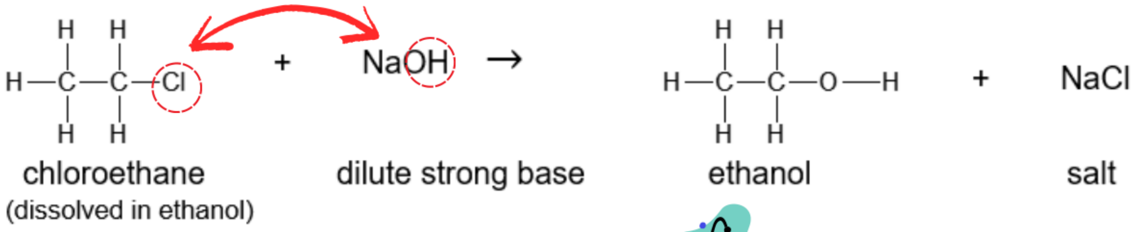
General hydrolysis reaction equation:

$$\text{haloalkane} + \text{dilute strong base (NaOH or KOH)} \longrightarrow \text{alcohol} + \text{salt}$$

Example

Chloroethane is dissolved in ethanol and reacted with dilute sodium hydroxide:

Balanced reaction using the structural formulae:



Balanced reaction using the molecular formulae:

$$C_2H_4Cl + NaOH \longrightarrow C_2H_5OH + NaCl$$

NOTE: During hydrolysis, a halogen atom in the haloalkane gets substituted (replaced) by a hydroxyl group.

Hydrolysis using water

The same hydrolysis reaction can occur using water instead, but at a much slower rate compared to if a dilute strong base was used.

Reaction conditions for a hydrolysis reaction using water:

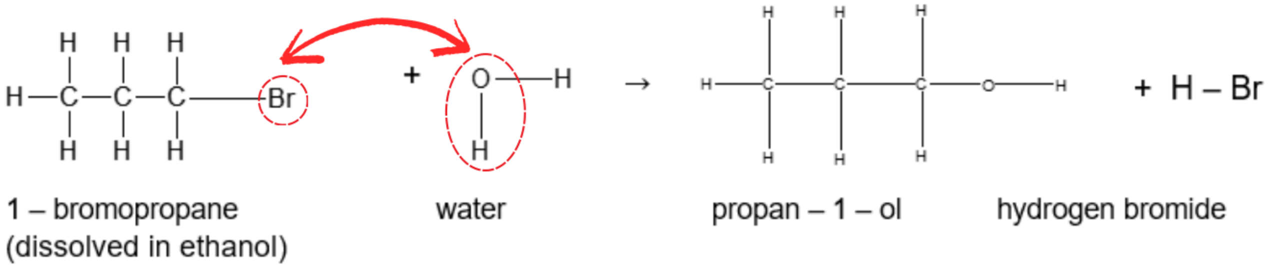
1. Water
2. Mild heat
3. Haloalkane dissolved in ethanol

General hydrolysis reaction equation:

Haloalkane + water ⟶ alcohol + hydrogen halide

Example

Balanced reaction using the structural formulae:



Balanced reaction using the molecular formulae:

$$C_3H_7Br + H_2O \longrightarrow C_3H_7OH + HBr$$

3.3 Substitution reaction: Alcohol to haloalkane [Alcohol reacts with a hydrogen halide (HX)]

Alcohols react with hydrogen halides (i.e. HCl, HBr) to form haloalkanes through a substitution reaction.

This substitution reaction works best with tertiary alcohols:
- Tertiary alcohols are converted into haloalkanes using a hydrogen halide (e.g., HBr or HCl) at **room temperature**
- Primary and secondary alcohols **react slowly** and at high temperature.

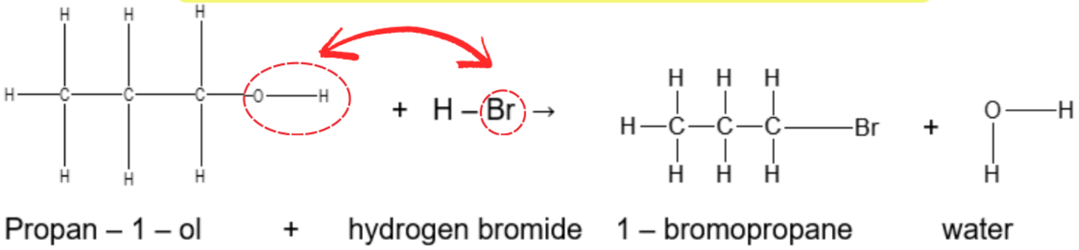
Reaction conditions:
1. High (strong) heat (for primary and secondary alcohols);
   Room temperature for tertiary alcohols (tertiary alcohols will react at room temperature).

General equation: Alcohol + hydrogen halide → haloalkane + water

Example

Propan-1-ol reacts with hydrogen bromide.

Balanced reaction using the structural formulae:



Balanced reaction using the molecular formulae:

$C_3H_7OH + HBr \rightarrow C_3H_7Br + H_2O$

4. Addition reactions

Addition reactions occur when atoms are **added** to a molecule, without the removal of any atoms. In order for an addition reaction to occur, the molecule must be **unsaturated**.

Addition reactions are undergone by alkenes. During an addition reaction, an alkene, unsaturated compound becomes a saturated compound, namely an alkane or alcohol or haloalkane.

There are 4 types of addition reactions:
1. Hydrohalogenation (alkene to haloalkane)
2. Halogenation (alkene to haloalkane)
3. Hydration (alkene to alcohol)
4. Hydrogenation (alkene to alkane)

PRO-TIPS

In an addition reaction, **only one** product (a saturated compound) is produced.

4.1 Hydrohalogenation (alkene to haloalkane)

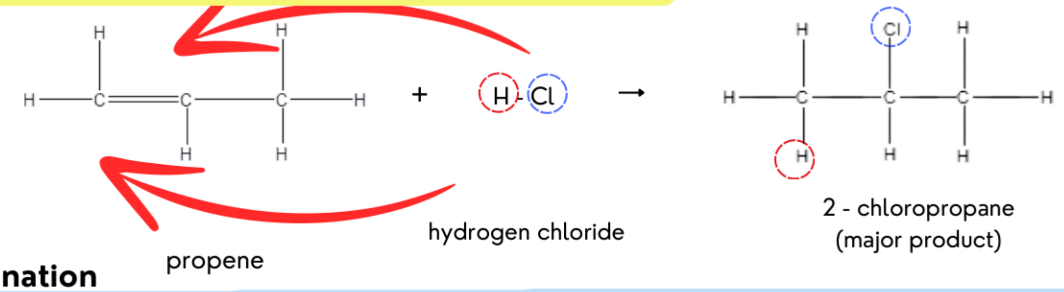
Hydrohalogenation is undergone by an alkene where the addition of a **hydrogen halide** (HX), e.g. HCl, HBr or HI results in the formation of a haloalkane as a product.
The double bond between the two carbon (C) atoms breaks, and the H-atom and halogen atom attach to the C atoms on either side.

Reaction conditions: Water- free hydrogen halide must be used.
(No water must be present to prevent the bonding with the –OH group).

Example

Hydrogen chloride reacts with propene.

Balanced reaction using the structural formulae:



Explanation

There are **two** possible products that can be produced in the reaction:

- Major product (2 - chloropropane) - this major product is more likely to be produced in this reaction.
- Minor product (1 - chloropropane) - this minor product is less likely to be produced in this reaction.

The **major product** i.e., the product that is most likely to be formed in an addition reaction, can be determined using Markovnikov's rule:

Markovnikov's rule: When a hydrogen atom is added to an unsaturated compound, the hydrogen atom is added to the carbon atom that already has the **most** hydrogen (H) atoms.

In this example, the double bond that is broken, lies between carbon 1 and carbon 2. Carbon 1 has more hydrogen atoms bonded to it than carbon 2, therefore according to Markovnikov's rule, the hydrogen atom will be added to carbon 1 and the chlorine atom to carbon 2.

Balanced reaction using the molecular formulae:

$$C_3H_6 + HCl \rightarrow C_3H_7Cl$$

PRO-TIPS

In a test or exam, always write the **major product**, unless asked to write the minor product.

4.2 Halogenation (alkene to haloalkane)

The addition of a halogen e.g. F_2, Cl_2, Br_2, I_2 to an alkene results in a haloalkane forming as a product.

The double bond between the two C atoms break and a halogen atom attaches to each of the C atoms that initially formed the double bond.

Reaction conditions: Reaction proceeds spontaneously at room temperature.

General equation:

$$\text{Alkene} + \text{halogen } (X_2) \rightarrow \text{haloalkane}$$

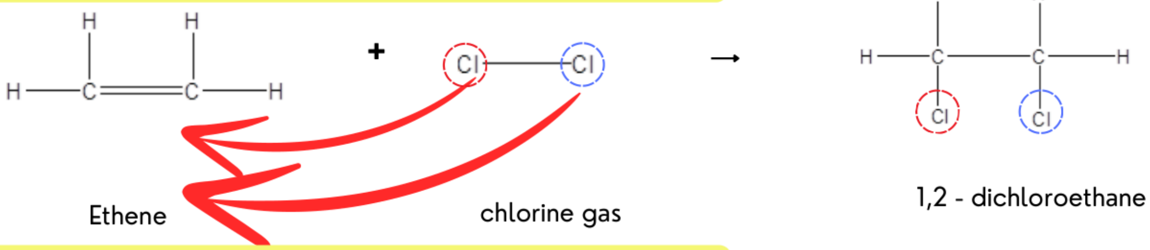
PRO-TIPS

In the "test for saturation", an alkene will react with bromine water spontaneously and **decolourise the bromine water** whereas an alkane will not react spontaneously.

Example

Ethene reacts with chlorine gas

Balanced reaction using the structural formulae:



Balanced reaction using the molecular formulae: $C_2H_4 + Cl_2 \rightarrow C_2H_4Cl_2$

4.3 Hydration (alkene to alcohol)

Hydration is the **addition of water** (H_2O) to an **alkene** to produce an **alcohol**.
The double bond between the two carbon (C) atoms break, and a hydrogen (H) atom and an -OH group attach to the carbon (C) atoms on either side.

Reaction conditions:

1. An **excess** of water.
2. **Catalyst:** A diluted strong acid such as sulphuric acid (H_2SO_4) or phosphoric acid (H_3PO_4)

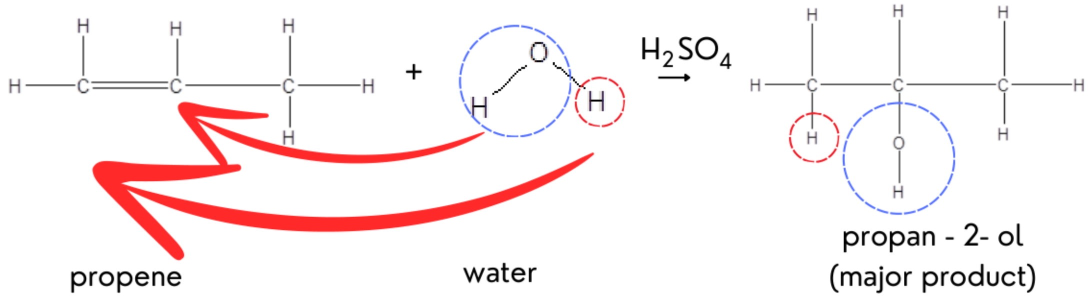
General equation:

$$\text{Alkene + water} \xrightarrow{\text{catalyst}} \text{alcohol}$$

Example

Propene reacts with water in the presence of a H_2SO_4 catalyst.

Balanced reaction using the structural formulae:



Remember: to determine the **major product**, apply Markovnikov's rule:

Balanced reaction using the molecular formulae:

$$C_3H_6 + H_2O \xrightarrow{H_2SO_4} C_3H_7OH$$

4.4 Hydrogenation (alkene to alkane)

Hydrogenation is the addition of hydrogen to an alkene (H) to produce an alkane.

Reaction conditions:

1. Use a catalyst such as Ni (Nickel), palladium (Pd) or Platinum (Pt).
2. Dissolve the alkene in a non – polar solvent.

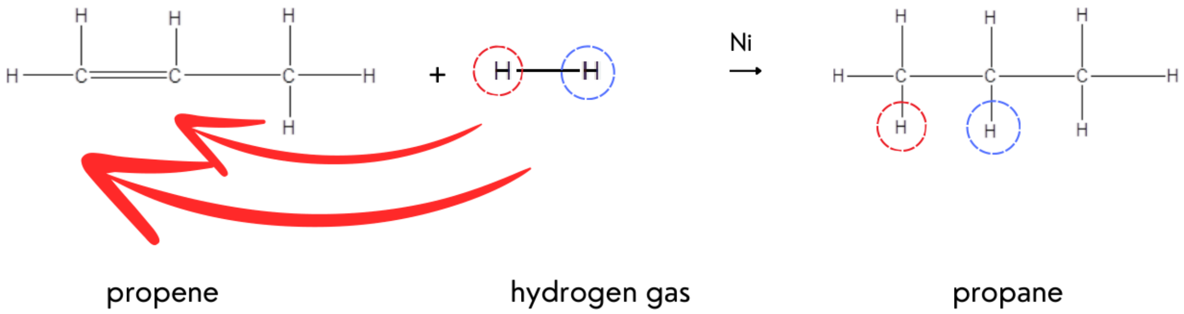
General equation for a hydrogenation reaction:

$$\text{Alkene + hydrogen} \xrightarrow{\text{catalyst}} \text{Alkane}$$

Example

Propene reacts with hydrogen gas in the presence of a Ni catalyst.

Balanced reaction using the structural formulae:

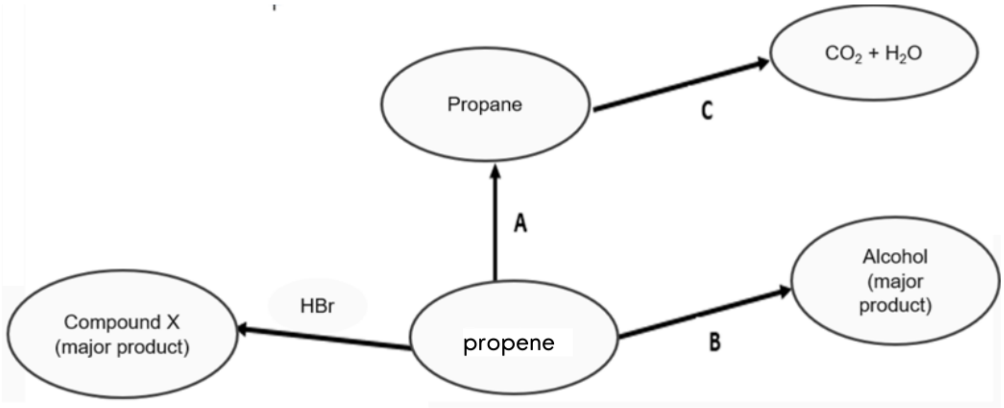


Balanced reaction using the molecular formulae:

$$C_3H_6 + H_2 \xrightarrow{Ni} C_3H_8$$

Worked example

The flow diagram below shows how propene can be used to prepare other compounds.



Write down the:

1.1 NAME or FORMULA of the catalyst needed for reaction **A**. (1)

1.2 NAME or FORMULA of the inorganic reagent needed for reaction **B.** (1)

1.3 Type of reaction represented by reaction **C**. (1)

1.4 Type of addition reaction represented by reaction **B.** (1)

1.5 IUPAC name of compound **X**. (2)

2. Use structural formulae to write down a balanced equation for reaction **B**. (5)

Analysis of organic reactions:
Reaction A: alkene to alkane: addition reaction (hydrogenation - addition of hydrogen)

Reaction B: Alkene to alcohol: Addition reaction (hydration - addition of water).

Reaction C: complete combustion reaction: Alkane reacts with oxygen to produce carbon dioxide and water.

Propene reacts with HBr to produce major product (haloalkane - compound X)

PRO-TIPS

When given a flow chart of organic reactions:
As far as possible, first analyse the flow chart first

1.1 Reaction **A** is an addition reaction, namely hydrogenation. The catalysts that can be used in this reaction:
Ni or Nickel/ Pd or palladium/Pt or platinum

1.2 Reaction **B** is an addition reaction, namely hydration. The reactant used must be water which has a -OH present to produce an alcohol.

H_2O or water

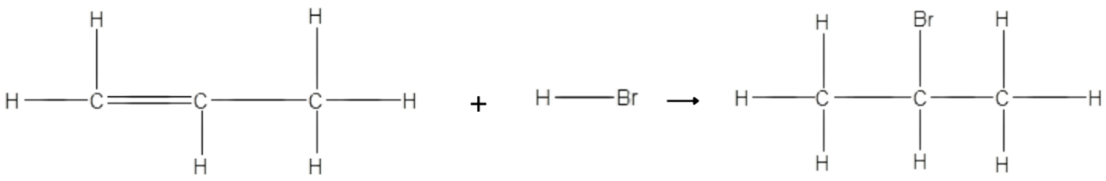
1.3 Reaction **C** is an alkane reacting with oxygen to produce carbon dioxide and water. (Complete) combustion reaction.

1.4 Reaction **B** is an addition reaction where an alkene is converted to an alcohol:
Hydration

1.5 Structural formula showing the formation of compound **X**:

PRO-TIPS

Draw the structural formula to get a visual representation of the product.



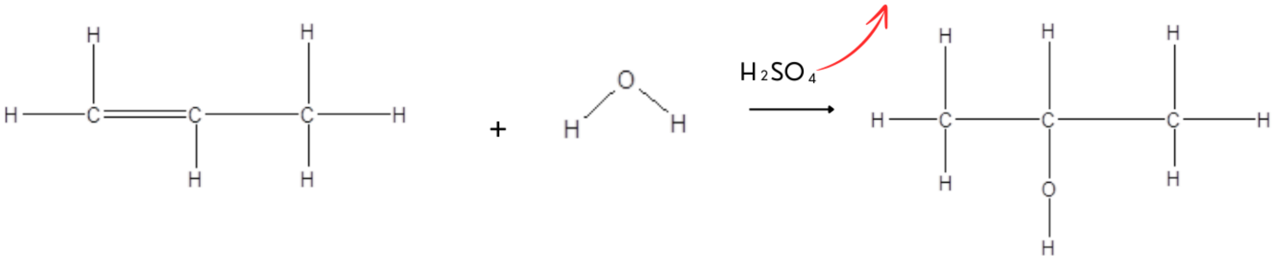
To determine the major product, apply Markovnicov's rule:
Markovnikov's rule: When a hydrogen atom is added to an unsaturated compound, the hydrogen atom is added to the carbon atom that already has the **most** hydrogen (H) atoms. Therefore the hydrogen atom will be added to carbon 1 and the bromine atom to carbon 2.

∴ 1 - bromopropane

2.

Hydration using water

NOTE:
Marking guideline: In other reactions involving the use of a catalyst, the catalyst does not have to be indicated above the arrow, except in esterification.



TIP: To determine the major product, apply Markovnicov's rule.

PRO-TIPS

When writing the structural formula, always make sure that every carbon has four bonds.

5. Elimination reactions

Elimination is the **removal** of atoms from a **saturated** compound (e.g., alkane or alcohol or haloalkane) to form an **unsaturated** compound (e.g., an alkene).
Elimination reactions are the **opposite** of **addition** reactions.
Elimination reactions are undergone by saturated compounds e.g. alkanes, haloalkanes and alcohols, to form unsaturated compounds.

General elimination reaction:
Saturated compound ⟶ unsaturated compound + inorganic byproduct

There are 3 types of elimination reactions:

1. **Cracking** (undergone by alkanes to form a shorter chained hydrocarbon/s i.e. an alkene and other by products)
2. **Dehydration** (water is eliminated/removed from an alcohol)
3. **Dehydrohalogenation** (elimination/removal of a hydrogen halide (H – X) from a haloalkane)

5.1 Cracking

Did you know?
Shorter chained molecules are more useful for fuels.

Definition: **Cracking**: The chemical process in which longer chain hydrocarbon molecules are broken down to shorter more useful molecules.

Reaction conditions for cracking:

There are two methods of cracking: Thermal cracking and catalytic cracking.

1. Thermal Cracking

Thermal cracking makes use of very high temperatures and high pressures, without a catalyst, to crack a longer chained hydrocarbon molecule into smaller and more useful molecules.

Thermal cracking reaction conditions: High heat and high pressure

2. Catalytic Cracking

Catalytic cracking involves lower temperatures and lower pressures than thermal cracking, and uses platinum as the catalyst.

Catalytic cracking reaction conditions: lower heat (than thermal cracking) and a catalyst, e.g. platinum (Pt)

Combination of products that can be produced in a cracking reaction:

- An alkane and an alkene

OR

- One or more alkenes + H_2 (hydrogen gas)

PRO-TIPS

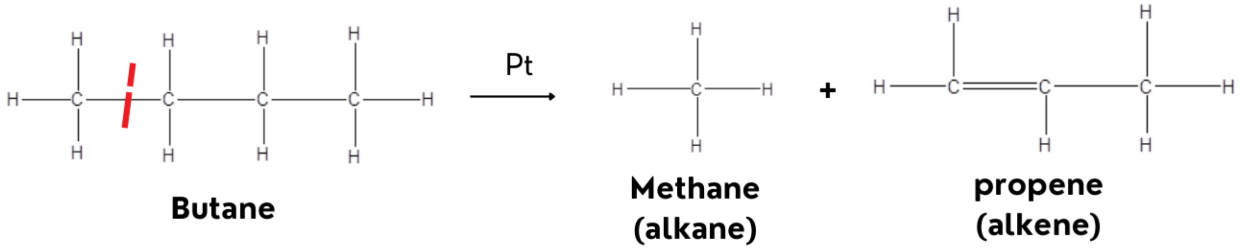
In a test or exam, questions are usually guided to determine which products are produced or reactants that reacted.

Example

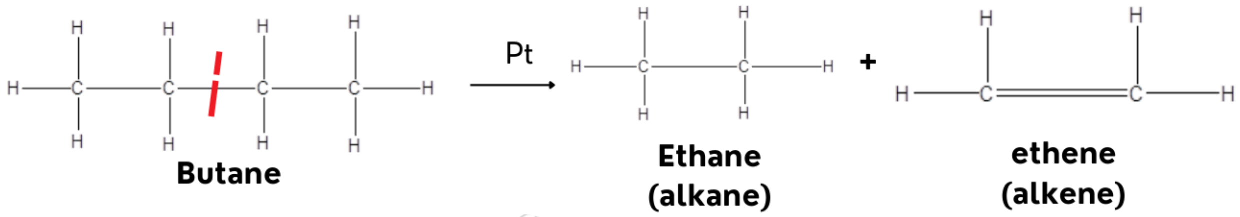
Write down the structural formulae of all the possible products produced when butane is cracked, using a platinum catalyst and heat.

There are **three** possible ways for butane to be cracked:

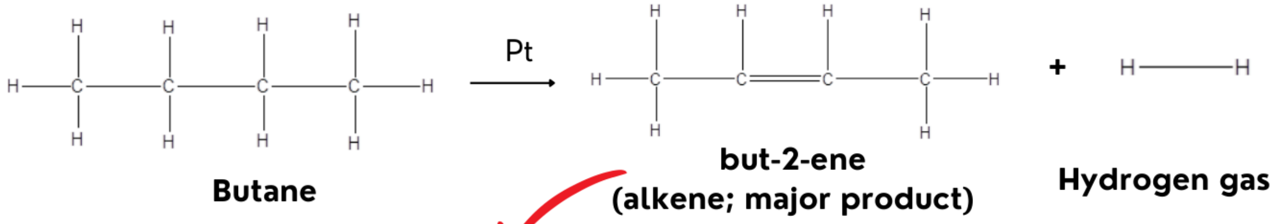
OPTION 1: Cracking between the CH_3 - CH_2 bond



OPTION 2: Cracking between the CH_2 - CH_2 bond



OPTION 3: Cracking the C - H bond (cracking off two Hydrogens)



In elimination reactions, **Zaitsev's rule** is applied to determine the major product:
Zaitsev's rule states that, in an elimination reaction, a hydrogen (H) atom is removed from the carbon (C) atom with the **least** number of hydrogen (H) atoms to produce the major product.

5.2 Dehydration

Dehydration is the elimination reaction where water (H_2O) is eliminated from an alcohol, to produce an alkene and water. Dehydration is the reverse process of hydration.

From Zaitsev's rule:
Major product: The reaction involves the elimination of the –OH group together with the removal of the hydrogen atom from the adjacent carbon atom with the least number of hydrogen (H) atoms. A double bond forms between these two carbon atoms.

Reaction conditions:

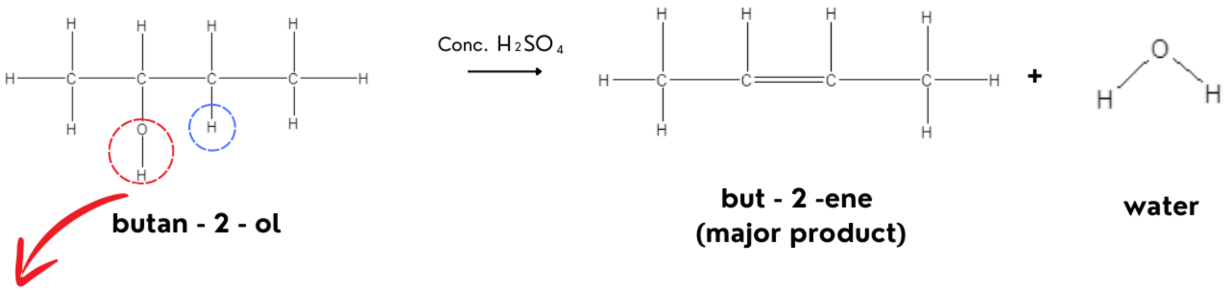
1. **Heat** the alcohol together with a **catalyst**: concentrated H_2SO_4 (sulphuric acid) or concentrated H_3PO_4(Phosphoric acid).

General equation: $$\text{Alcohol} \xrightarrow{\text{Conc.}H_2SO_4 \text{ OR Conc. } H_3PO_4} \text{alkene + water}$$

Example

Butan- 2 - ol is heated with a concentrated sulphuric acid

Balanced reaction using the structural formulae:



Apply Zaitsev's rule:
Major product: The reaction involves the elimination of the –OH group together with the removal of the hydrogen atom from the adjacent carbon atom with the least number of hydrogen (H) atoms. A double bond forms between these two carbon atoms.

Balanced reaction using the molecular formulae: $C_4H_9OH \xrightarrow{\text{Conc. } H_2SO_4} C_4H_8 + H_2O$

5.3 Dehydrohalogenation

Elimination reaction where a halogen (halide) atom, **X**, (e.g. Cl, Br, I etc.) is removed together with a hydrogen (H) atom of an adjacent carbon (C) atom from a haloalkane.

General equation for a dehydrohalogenation reaction:

Haloalkane + concentrated strong base ⟶ alkene + salt + water

From Zaitsev's rule: Major product: The reaction involves the elimination of the halogen atom together with the removal of the hydrogen atom from the adjacent carbon atom with the **least** number of hydrogen atoms.
A double bond forms between these two carbon atoms.

Reaction conditions:

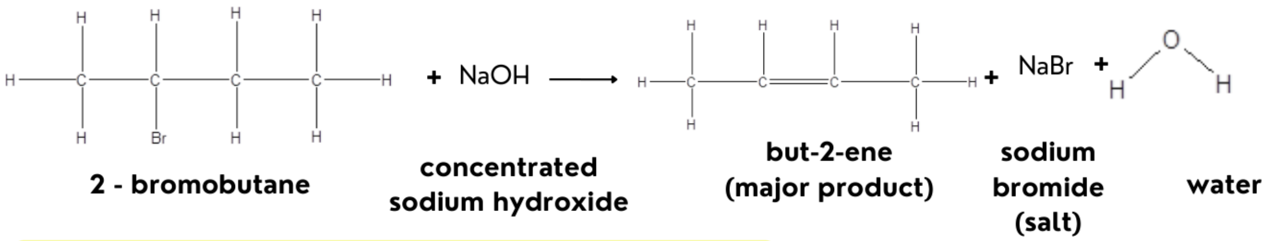
1. CONCENTRATED strong base, e.g., concentrated NaOH/KOH/ LiOH dissolved in ethanol
2. Heat under reflux **or** high heat.

Heat under reflux:
The heating is done under reflux - meaning that the substance is heated, the vapours then condense, return to the reaction vessel and are heated again.

Example

2 – bromobutane reacts with concentrated sodium hydroxide.

Balanced reaction using the structural formulae:



Balanced reaction using the molecular formulae:

$$C_4H_9Br + NaOH \longrightarrow C_4H_8 + NaBr + H_2O$$

Worked example

C + A

Multiple choice question

Organic compound **X** is produced in industry by the THERMAL CRACKING of long chain hydrocarbons as indicated in the equation below.

$$C_{10}H_{22} \rightarrow C_6H_{12} + \mathbf{X}$$

Which ONE of the following represents the IUPAC name of compound **X**?

A butane

B but-1-ene

C but-1-yne

D butan-1-ol

Answer: A

$C_{10}H_{22}$ is an alkane, that has undergone thermal cracking. From the equation given, two products are formed in the cracking of $C_{10}H_{22}$.

In a chemical reaction, the law of conservation of mass applies. Therefore, the number of atoms of each element in the reactants, must equal the number of atoms of each element in the products.

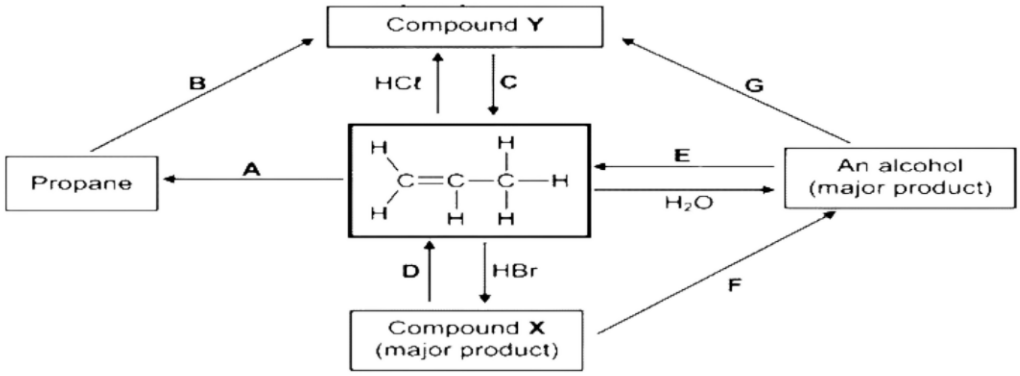
One of the products has the chemical formula C_6H_{12} (an alkene), therefore, since there are 10 carbon atoms and 22 hydrogen atoms in the reactant, compound **X** will have 4 carbon atoms (10 - 6 = 4) and 10 hydrogen atoms (22-12 = 10):

C_4H_{10}, this is an alkane, namely butane, since it follows the general rule for alkanes, namely C_nH_{2n+2}

Worked example

A + P

The flow diagram below shows how an alkene can be used to prepare other organic compounds. The letters **A** to **G** represent different organic reactions.



1.1 Write down the type of reaction represented by:

1.1.1 **A** (1)

1.1.2 **B** (1)

1.1.3 **E** (1)

1.2 Write down the IUPAC name of compound **X**. (2)

1.3 For reaction **D**, write down:

1.3.1 The type of elimination reaction. (1)

1.3.2 TWO reaction conditions. (2)

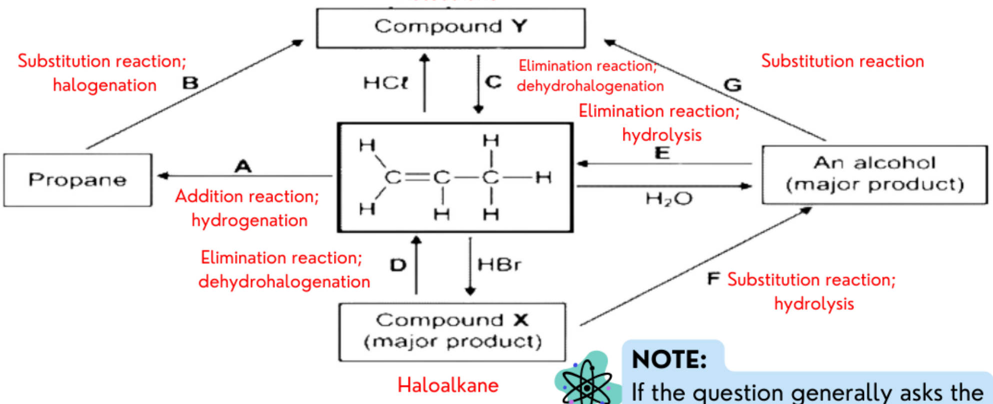
1.4 Write down the:

1.4.1 FORMULA of an inorganic reactant needed for reaction **F**. (1)

1.4.2 Balanced equation, using structural formulae, for reaction **G**. (4)

TIP: Analyse reaction A - F before answering the questions that follow. Write this analysis on the flow diagram:

Reaction **A**: An alkene, propene, is converted into propane. A unsaturated compound is being converted into a saturated compound. This is an **addition reaction, namely hydrogenation**.
Reaction **B**: Compound **Y** needs to first be determined, to determine what type of reaction reaction B is. Compound Y is formed when an alkene, propene, reacts with HCl (a hydrogen halide), therefore through this addition reaction, compound **Y** is a haloalkane. In reaction **B**, an alkane, propane, is being converted into a haloalkane. This is a saturated compound being converted into another saturated compound, therefore it is a **SUBSTITUTION** reaction, namely halogenation.
Reaction **C**: A haloalkane is being converted into an alkene. This is a saturated compound being converted into a unsaturated compound, therefore, it is a **ELIMINATION** reaction, namely dehydrohalogenation.
Reaction **D**: Compound **X** needs to first be determined, to determine what type of reaction reaction **D** is. Compound **X** is formed when an alkene, propene, reacts with HBr (a hydrogen halide), therefore, through this addition reaction, compound **X** is a haloalkane. In reaction **D**, a haloalkane is being converted into a alkene. This is a saturated compound being converted into a unsaturated compound, therefore it is an **ELIMINATION** reaction, namely dehydrohalogenation.
Reaction **E**: An alcohol is being converted into an alkene. This is a saturated compound being converted into a unsaturated compound, therefore, it is an **ELIMINATION** reaction, namely dehydration.
Reaction **F**: A haloalkane is converted into a alcohol. This is a saturated compound being converted into another saturated compound, therefore it is a **SUBSTITUTION** reaction, namely hydrolysis.
Reaction **G**: An alcohol is converted into a haloalkane. This is a saturated compound being converted into another saturated compound, therefore it is a **SUBSTITUTION** reaction.



NOTE:
If the question generally asks the **type of reaction**, either substitution/ addition/ elimination will be accepted **OR** the specific type of substitution/addition/elimination reaction.

1.1.1 Reaction **A** is an alkene being converted into an alkane.
∴Addition reaction/hydrogenation

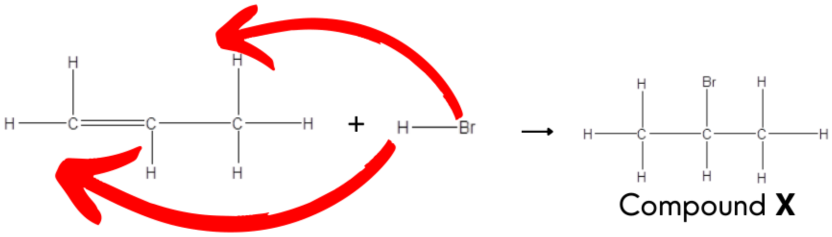
1.1.2 In reaction **B**, an alkane, propane, is being converted into a haloalkane.
∴Substitution reaction/ halogenation/chlorination.

NOTE: Chlorine is substituted into the alkane, this can also be described as chlorination.

1.1.3 An alcohol is being converted into an alkene.
∴Elimination reaction/dehydration.

1.2 **Tip:** Write a balanced chemical reaction using the structural formulae. To determine the major product, apply Markovnicov's rule:

Markovnikov's rule: When a hydrogen atom is added to an unsaturated compound, the hydrogen atom is added to the carbon atom that already has the **most** hydrogen (H) atoms. In this question that is carbon **1**.


Compound **X**

Compound **X** is 2 - bromopropane

1.3.1 In reaction **D**, a haloalkane is being converted into an alkene.
∴Dehydrohalogenation/dehydrobromination.

NOTE: A bromine and hydrogen atom is removed from the haloalkane, this can also be described as dehydrobromination

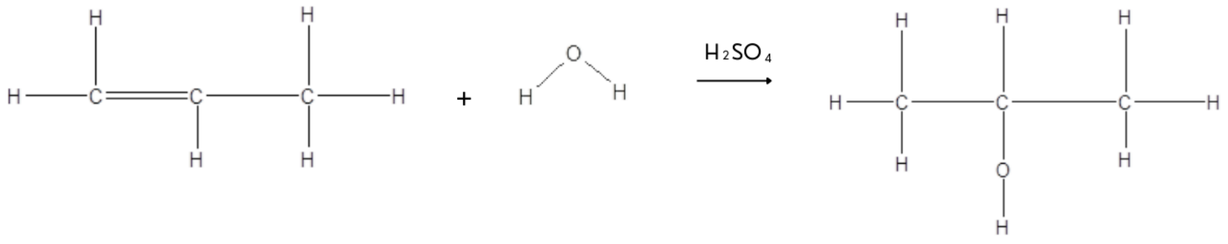
1.3.2 Dehydrohalogenation is an elimination reaction which requires the following reaction conditions:
1. CONCENTRATED strong base, e.g., concentrated NaOH/KOH/ LiOH dissolved in ethanol
2. Heat under reflux **or** high heat.

1.4.1 In reaction **F**, a haloalkane is converted into a alcohol. A reactant containing a hydroxide ion/hydroxyl group is required:
H_2O **or** (dilute) NaOH/KOH/LiOH

NOTE: The NAME of at least one of these substances must be stated.

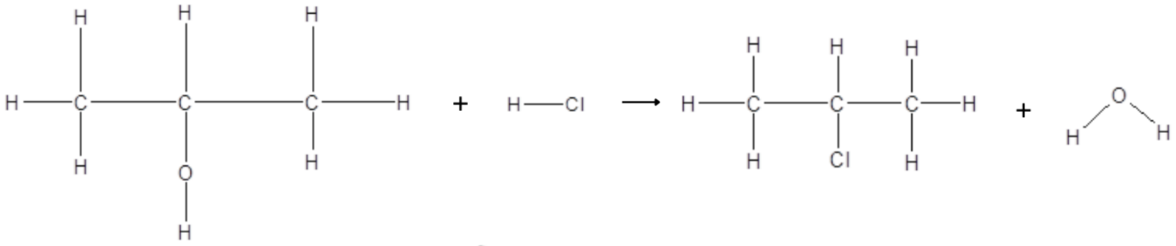
1.4.2

Before the reaction for reaction **G** can be written, the alcohol (reactant) in reaction **G** needs to be determined. Propene (alkene) reacts with water, this is an addition reaction. Apply Markovnikov's rule:

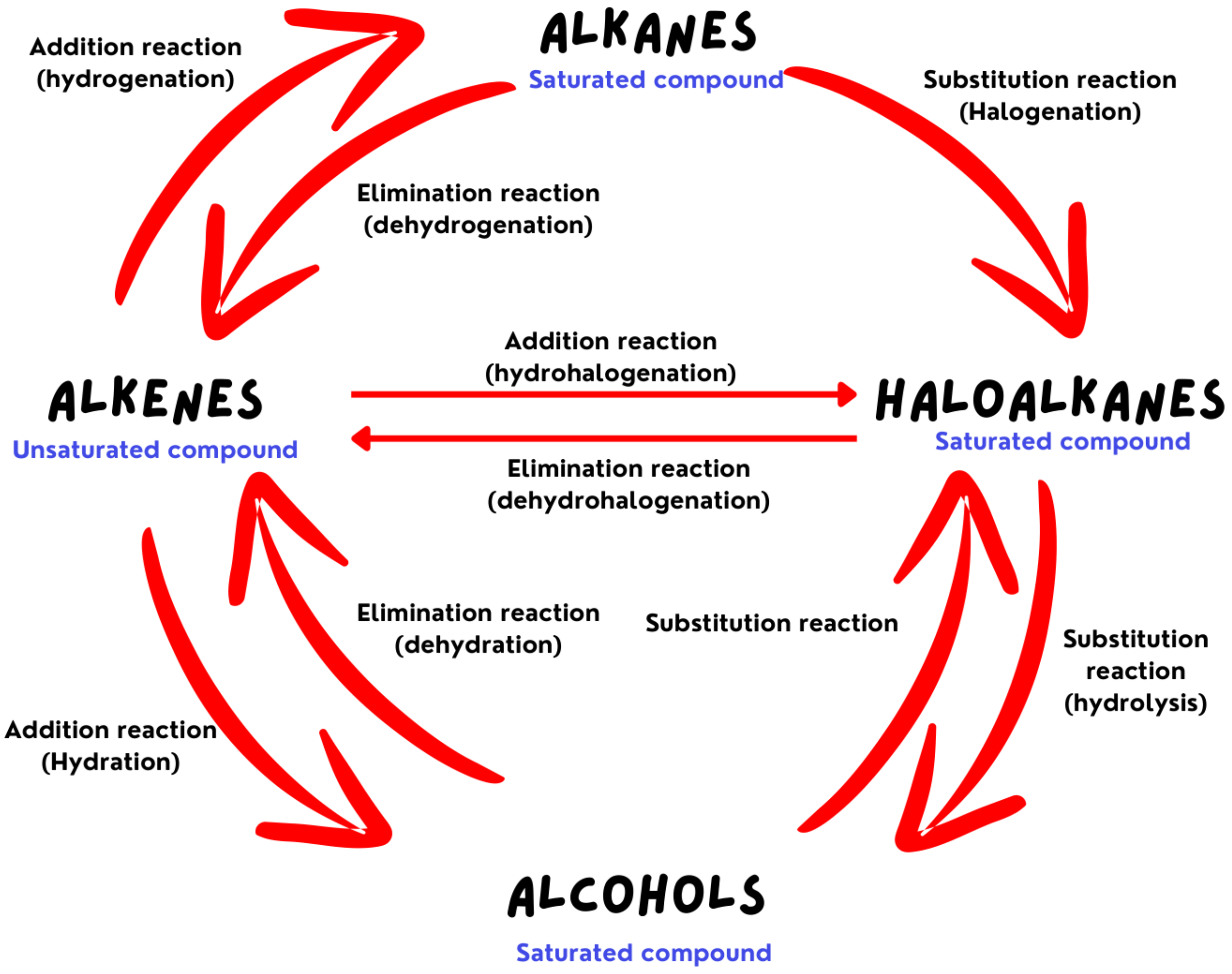


propan-2-ol

In reaction **G**, an alcohol (propan - 2 - ol) is converted into a haloalkane (2 - chloropropane). This is a saturated compound being converted into another saturated compound, therefore it is a SUBSTITUTION reaction.
The hydroxyl group is replaced (substituted) by a halogen atom. In this reaction, a haloalkane and an inorganic by product, water is produced:



SUMMARY OF THE ORGANIC REACTIONS



ALKANES
Saturated compound

Addition reaction
(hydrogenation)

Elimination reaction
(dehydrogenation)

Substitution reaction
(Halogenation)

ALKENES
Unsaturated compound

Addition reaction
(hydrohalogenation)

Elimination reaction
(dehydrohalogenation)

HALOALKANES
Saturated compound

Elimination reaction
(dehydration)

Substitution reaction

Addition reaction
(Hydration)

Substitution
reaction
(hydrolysis)

ALCOHOLS
Saturated compound

REMINDER :QUESTION DIFFICULTY

C — **COMPREHENSION AND RECALL QUESTIONS**

These are common questions which include definitions and calculation questions that look similar to the questions covered in class. Approximately **50%** of Paper 1 (Physics) will include questions on this level.

A — **ANALYSIS AND APPLICATION QUESTIONS**

These are more complex questions which involves applying the knowledge and skills learned in this chapter. Approximately **40%** of Paper 1 (Physics) will include questions on this level.

P — **PROBLEM- SOLVING QUESTIONS**

These are questions that require critical thinking and being able to make connections between different representations of information and integrating different topics. They are not familiar questions, but are able to be solved through critical analysis. Approximately **10%** of Paper 1 (Physics) will include questions on this level.

RATE AND EXTENT OF REACTION:
REACTION RATES

In reality, some reactions such as combustion reactions occur very quickly, while others such as the ripening of fruit occurs slowly. The **rate** of a chemical reaction simply refers to how **fast** (or **slow**) a chemical reaction takes place. However, the rate of a chemical reaction is affected by many factors such as **temperature**, the **concentration** (of reactants), **pressure** (in the case of gases), the **surface area** of solids, the use of **catalyst** and the **nature** of the reacting substances.

The collision theory and reaction rates

In order for a chemical reaction to occur between atoms, ions or molecules, they must collide. Not all collisions result in a reaction. In some cases, the colliding molecules frequently just bounce off each other unchanged.
A collision which results in a reaction is called an **effective collision.**

NOTE: A reaction can only occur if the collision is an effective collision.

According to the collision theory, for a chemical reaction to take place, the molecules must collide with:

✓ 1. the correct orientation
✓ 2. a sufficient amount of kinetic energy ($E_k \geq E_a$; i.e., a kinetic energy greater than or equal to the activation energy).

NOTE: As the **number of <u>effective collisions per unit time</u> increases, the rate of a chemical reaction increases.** The words "effective" and "per unit time" are important.

NOTE: Per unit time, refers to to rate, and can be replaced with "per second" or "per minute" etc.

What is the collision theory?

Definition: Collision theory: The collision theory is a model that explains reaction rate as the result of particles colliding with a certain minimum energy.

1.The correct orientation

According to the collision theory, molecules must collide with the correct orientation for the collision to be an effective collision. In **figure 1** below, two collisions that might take place between carbon monoxide and oxygen molecules is shown. The orientation of the colliding molecules is one factor that determines whether a reaction between the two molecules will occur or not.

Collision 1: The oxygen molecule collides with the oxygen end of the carbon monoxide molecule

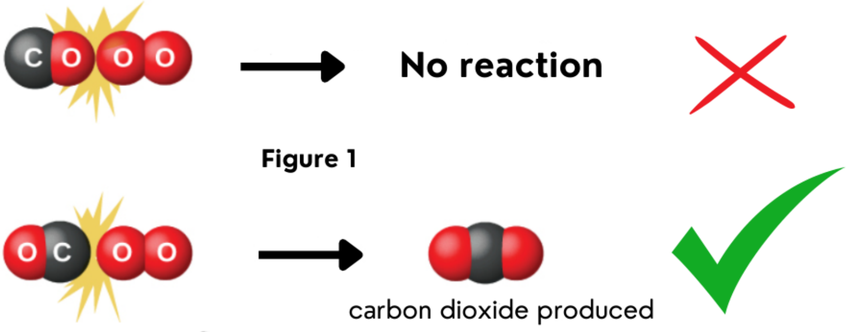


Figure 1

Collision 2: The oxygen molecule collides with the oxygen end of the carbon monoxide molecule

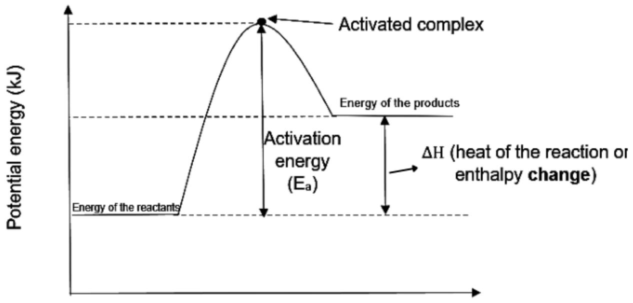
2.Sufficient kinetic energy

According to the collision theory, the molecules must collide with a sufficient amount of kinetic energy ($E_k \geq E_a$; i.e., a kinetic energy greater than or equal to the activation energy).

A potential energy versus reaction progress/reaction - co ordinate/course of reaction graph is represented below:

Endothermic reaction

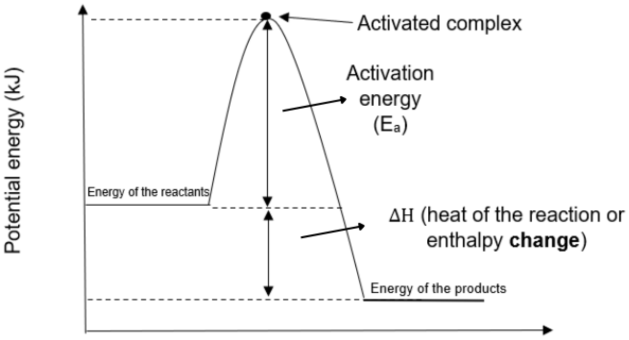
- An endothermic reaction is a chemical reaction that absorbs energy
- In an endothermic reaction, more energy is absorbed than released.



Reaction co-ordinate/course of the reaction progress

Exothermic reaction

- An exothermic reaction is a chemical reaction that releases energy
- In an exothermic reaction, more energy is released than absorbed.



Reaction co-ordinate/course of the reaction progress

Graph terminology

Activation energy (E_a): Minimum energy needed for a reaction to take place.
Activated complex: The unstable transition state from reactants to products in a chemical reaction.

Enthalpy change OR the heat of the reaction (ΔH): The energy absorbed or released during a chemical reaction.

Calculating the enthalpy change or heat of the reaction (△H):

$\triangle H = E_{products} - E_{reactants}$ **OR** $\triangle H = H_{products} - H_{reactants}$

Endothermic reaction: $\triangle H > 0$

Enthalpy change is positive; more energy is absorbed than released.

Exothermic reaction: $\triangle H < 0$

Enthalpy change is negative; more energy is released than absorbed.

Using the collision theory to explain the factors that affect the rate of a chemical reaction

According to the collision theory, there are five factors that affect the rate of a chemical reaction:

1. Concentration of reactants (solutions) or pressure (in the case of gaseous reactants)
2. Temperature
3. Surface area of solids.
4. Use of a catalyst
5. Nature of the reacting substances

Changing these conditions changes the rate of a reaction. This can be explained using the collision theory.

1 Concentration of reactants (solutions)

In many chemical reactions, the rate of a reaction is fastest at the start of the reaction when the concentration of the reactants is highest.

Using the collision theory to explain how the concentration of reactants affects the reaction rate:

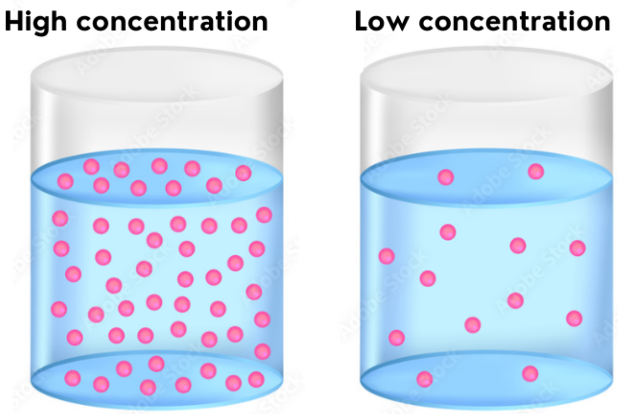
- The greater the concentration of the reactants, the greater the number of moles of reacting particles per unit volume.
- ∴ More particles have a sufficient amount of kinetic energy ($E_k \geq E_a$) to react.
- ∴ There will be <u>more effective collisions per unit time.</u>
- ∴ The reaction rate increases.

OR

- The lower the concentration of the reactants, the smaller the number of moles of reacting particles per unit volume.
- ∴ Less particles have a sufficient amount of kinetic energy ($E_k \geq E_a$) to react.
- ∴ There will be <u>fewer/less effective collisions per unit time.</u>
- ∴ The reaction rate decreases.

Figure 2 below represents two solutions: one solution with a high concentration and a solution with a low concentration. Assume that the volume of the solutions is the same.

Figure 2



Greater number of moles of solute per unit volume.

Smaller number of moles of solute per unit volume.

NOTE:
Changing the volume of a solution of the **same concentration** does NOT change the reaction rate. This is because the concentration of the solution does not change; therefore, the ratio of the number of moles (of solute) to the volume of solvent remains constant.

1 Pressure of gaseous reactants

Using the collision theory to explain how the pressure of gaseous reactants affects the reaction rate:

- The higher the pressure of the gaseous reactants, the greater the force per unit area.
- The particles are forced closer together.
- ∴ there will be more effective collisions per unit time.
- ∴ the reaction rate increases.

OR

- The higher the pressure of the gaseous reactants, the greater the force per unit area.
- The particles are forced closer together.
- ∴ there will be more effective collisions per unit time.
- ∴ the reaction rate increases.

PRO-TIPS

Only gases are affected by a change in pressure.

2 Temperature

Definition: **Temperature:** A measure of the average kinetic energy of the particles in a substance.

Using the collision theory to explain how temperature affects the reaction rate:

- Increasing the temperature of a substance increases the average kinetic energy of the particles.
- ∴ More particles will now have a sufficient amount of kinetic energy ($E_k \geq E_a$) to react.
- ∴ The number of effective collisions per unit time increases and the rate of the reaction increases.

OR

- Decreasing the temperature of a substance decreases the average kinetic energy of the particles.
- ∴ Less particles will now have a sufficient amount of kinetic energy ($E_k \geq E_a$) to react.
- ∴ The number of effective collisions per unit time decreases and the rate of the reaction decreases.

3 Surface area of solids

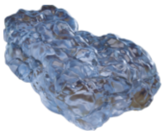
Compare a powdered solid to a solid chunk or lump of the **same substance of the same mass:**

Powdered solid

Covers a greater surface area compared to a solid chunk of the same mass.

VS

Solid chunk or lump



Covers a smaller surface area compared to the powdered substance of the same mass.

Using the collision theory to explain how the surface area of solids affects the reaction rate:

- The greater the surface area of the solid (i.e., a powdered solid) the greater the exposed reacting surface.
- ∴More particles will collide with the correct orientation.
- ∴The <u>number of effective collisions per unit time increases.</u>
- ∴ The reaction rate increases.

OR

- The smaller the surface area of the solid (i.e., a chunk or lump of solid) the smaller the exposed reacting surface.
- ∴Fewer/less particles will collide with the correct orientation.
- ∴The number of effective collisions per unit time increases.
- ∴The reaction rate deccreases.

4 Use of a catalyst

What is a catalyst?

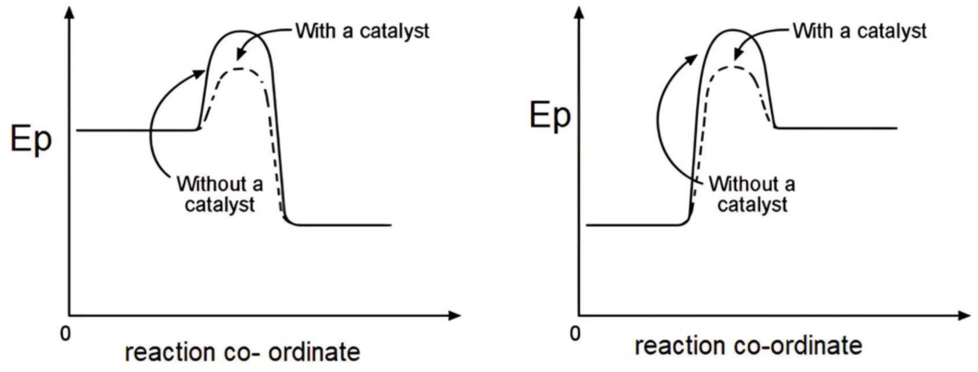
Definition: **Catalyst**: A substance that increases the rate of a chemical reaction without itself undergoing a permanent change.

- This is also called a positive catalyst. A positive catalyst is a substance which is added to a reaction mixture in order to increase the rate of the reaction
- The catalyst is not used up during the reaction. It does not change the reaction stoichiometry or the equilibrium extent of the reaction.

How does a catalyst work?

- A catalyst acts as an intermediate and gets those reactant molecules which initially did not have enough kinetic energy to react, to now react.
- **Adding a catalyst does not change the average kinetic energy of the particles**, instead, by it getting those reactant molecules which initially did not react, to now react, in doing so, it **lowers the activation energy of the reaction and provides an alternative pathway (of lower activation energy) for the reaction to take place.**

Figure 3 below represents the effect of catalyst, using a dotted line to represent how the activation energy is lowered in an exothermic reaction and an endothermic reaction:


Exothermic reaction **Endothermic reaction**

Using the collision theory to explain the effect of adding a catalyst on the reaction rate.

- Adding a catalyst increases the rate of a reaction by lowering the activation energy and providing an alternative pathway of lower activation energy for the reaction to take place.
- ∴ more molecules now have a sufficient amount kinetic energy ($E_k \geq E_a$) to react.
- ∴ there will be more effective collisions per unit time and the reaction rate increases.

5 The nature of the reacting substances

What determines the reactivity of substances?

- The **reactivity** of a substance is determined by:

1. the **number** of **bonds**
2. the **strength** of the bond
3. the **type** of bond
4. the **amount** of **activation** energy required to break the bonds.

- Simple substances with weak bonds and a lower activation energy react faster than complex molecules with stronger bonds.

Examples of the reactivity of substances

- Some substances are more reactive than others– for example, oxygen gas is much more reactive than nitrogen gas. Oxygen reacts readily with many other substances, while nitrogen is very unreactive.
- Reactions involving simple ions often occur more instantaneously and at a faster rate than reactions involving molecules. This is because positive and negative ions attract each other, and no bonds have to be broken. However, with reactions involving molecules, the bonds of those molecules first need to be broken and new bonds formed. This slows down the reaction rate and results in fewer effective collisions per unit time taking place between the molecules, compared with the collisions that take place between ions.

PRO-TIPS

When using the collision theory to explain the factors affecting the reaction rate, the above modal answers can be used as a guidelines. The words "**effective** collisions **per unit time**" cannot be omitted.

Worked example

Multiple choice question

A small amount of zinc powder is placed in a test tube and covered with dilute sulphuric acid. Which ONE of the following will **not** affect the rate of the reaction?

A Heating the test tube
B Using zinc granules instead of zinc powder
C Adding a larger volume of the dilute acid
D Adding concentrated acid instead of dilute acid.

Answer: C

✓ In option **C**: Increasing the volume of the dilute acid of the **same concentration** results in the ratio of the number of moles of solute to the volume of solvent remaining constant, therefore, the reaction rate remains constant.

✗ in option **A**: Heating the test tube (i.e., increasing the temperature of the reaction mixture) increases the kinetic energy of the particles, therefore more particles have a sufficient amount of kinetic energy to react, reaction rate increases.

✗ In option **B,** zinc granules cover a smaller surface area compared to powdered zinc of the same mass, therefore using zinc granules instead of zinc powder decreases the number of effective collisions per unit time, therefore the reaction rate decreases.

✗ In option **D,** if the concentration of the solution is increased, this increases the number of moles of reacting particles per unit volume, therefore more particles have a sufficient amount of kinetic energy to react and there are more effective collisions per unit time.

Measuring and calculating the rate of a chemical reaction

The term "rate" can be defined as amount per second, and generally gives an indication of how a physical quantity changes with time.

$$\text{Rate} = \frac{1}{\Delta t}$$

PRO-TIPS

- The formula used to calculate the reaction rate, depends on information given and asked.
- The units of in which the reaction rate is usually specified in the question.

The rate of a chemical reaction can be defined as:

Definition: **Rate of reaction:** Change in concentration of reactants or products per unit time.

OR

Definition: Rate of reaction: Change in the amount/ number of moles/volume/mass of reactants or products per unit time.

Reaction rate is a **scalar quantity**, therefore it has magnitude only and is always positive. The average rate of a chemical reaction can be measured using ONE of the following formulae (derived from the above definitions of reaction rate):

Reactants

$\text{Rate} = -\left(\frac{\Delta c}{\Delta t}\right)$

$\text{Rate} = -\left(\frac{\Delta n}{\Delta t}\right)$

$\text{Rate} = -\left(\frac{\Delta m}{\Delta t}\right)$

$\text{Rate} = -\left(\frac{\Delta V}{\Delta t}\right)$

NOTE: In a chemical reaction, **reactants** get used up as the reaction proceeds, therefore the final amount after a time period is less than the initial amount at the start of the time period. Since the rate of a chemical reaction is always positive, the negative sign ensures this.

NOTE: In a chemical reaction, **products** are formed as the reaction proceeds, therefore the final amount after a time period is greater than the initial amount at the start of the time period.

Products

$\text{Rate} = \left(\frac{\Delta c}{\Delta t}\right)$

$\text{Rate} = \left(\frac{\Delta n}{\Delta t}\right)$

$\text{Rate} = \left(\frac{\Delta m}{\Delta t}\right)$

$\text{Rate} = \left(\frac{\Delta V}{\Delta t}\right)$

REVISION OF STOICHIOMETRY

Stoichiometry It is the branch of chemistry that deals with **quantities in chemical reaction.**

The mole concept

What is a 'mole'?

Definition: Mole: SI unit for the amount of substance.
Definition: One mole: The amount of substance having the same number of particles as there are atoms in 12 g carbon – 12.

In **one mole of any substance** there is $6{,}02 \times 10^{23}$ particles. This is called Avogadro's constant
(N_A)

$$N_A = 6{,}02 \times 10^{23} \text{ mol}^{-1}$$

$$n = \frac{N}{N_A} \text{ (on data sheet)}$$

What do these variables mean and what are the SI units?

N = number of particles (atoms or molecules or ions or formula units)
N = Avogadro's constant or Avogadro's number.
$6{,}02 \times 10^{23}$ mol^{-1}
n = number of moles (of a substance) in moles (mol).

Molar mass and number of moles

Molar mass (M): Mass of one mole of a substance.

SI units: g.mol^{-1}

Formula to interchange between mass and number of moles:

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

What do these variables mean and what are the SI units?

n = number of moles (of a substance) in moles (mol).
m = mass of a substance in grams (g)
M = molar mass in g.mol^{-1}

Empirical formula vs molecular formula

Empirical formula: Chemical formula that shows the **simplest whole number ratio of atoms** in a compound.

VS

Molecular formula: Chemical formula that shows the ACTUAL whole- number ratio of the atoms in a compound.

Example: Glucose has the chemical formula: $C_6H_{12}O_6$ →

Molecular formula of glucose

The molecular formula can be simplified; i.e., the ratio in which the atoms actually bond can be simplified to:

CH_2O →

Empirical formula of glucose

Divide the number of moles of each atom by 6.

Concentration of solutions (c)

What is a solution?

When a solute dissolve in a solvent, a solution is formed. It is the homogeneous mixture of two or more substances.

What is the concentration of a solution?

Concentration (of a solution) is the number of moles of solute per cubic decimeter (per litre) of solution; it is the ratio of the number of moles of solute to the volume of solvent.

$$\boxed{c = \frac{n}{V}}$$

OR

Formula that can be used if the mass of solute is known:

$$\boxed{c = \frac{m}{MV}}$$

What do these variables mean and what are the SI units?

n = number of moles (of a substance) in moles (mol).
m = mass of a substance in grams (g)
M = molar mass in $g.mol^{-1}$
V = volume of solvent or volume of the solution in dm^3
c = concentration of the solution in $mol.dm^{-3}$

PRO – TIPS

Volume conversion chart

$cm^3 \rightarrow dm^3$	÷ 1000
$m^3 \rightarrow dm^3$	× 1000
$ml \rightarrow dm^3$	÷ 1000

NOTE: 1 ml = 1 cm^3
1 litre = 1000 ml = 1 dm^3

Molar gas volume of gases

Avogadro's Law: One mole of any gas occupies the same volume at the same temperature and pressure.

At STP, standard temperature and pressure, namely:

- Standard temperature of 0°C or 273 K (or 273, 15 K)
- Standard pressure of 101, 3 kPa or 1 atmosphere (atm)

ONE mole of any gas occupies a volume of 22,4 dm^3. This is called the molar gas volume (V_m) at STP and is expressed as 22,4 $dm^3.mol^{-1}$ on the data sheet.

NOTE: If the temperature and/or pressure of the gas is changed, the molar gas volume will change, since the conditions are no longer at STP. If the molar gas volume changes, the changed molar gas volume must be specified, otherwise always use 22,4 $dm^3.mol^{-1}$ if the conditions are at STP.

Formula to calculate the volume of a gas:

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

What do these variables mean and what are the SI units?

n = number of moles (of gas) in moles (mol).
V = volume of gas in dm^3
V = molar gas volume (22,4 $dm^3.mol^{-1}$at STP).
NOTE: The molar gas volume can change as the temperature and/or pressure of the gas changes.

Chemical reactions: mole ratios

Stoichiometry is the calculation of the quantities (mass, volume, moles etc.) of reactants and products in chemical reactions. We can use the mole ratios from a **BALANCED** chemical reaction to do calculations.

Example: $N_2(g) + 3H_2(g) \rightarrow 2\ NH_3(g)$

The coefficients represent the number of moles and the mole ratio in which substances react completely with each other.

The reaction can be interpreted as:

For every 1 mole of $N_2(g)$ that reacts with 3 moles of $H_2(g)$, 2 moles of NH_3 (g) is produced.

PRO - TIPS

Initially work with the number of moles in these questions. Where necessary, convert all masses/volumes/concentration of solutions to moles.

Worked examples

C + A

1. Hydrogen gas reacts with oxygen gas, to produce water, according to the following balanced reaction:

$$2H_2(g) + O_2(g) \rightarrow 2H_2O\ (l)$$

6,4 g of oxygen reacts completely with excess hydrogen. Calculate:

1.1 the mass of H_2O produced. (4)
1.2 the volume of H_2 reacted, if the reaction takes place at STP. (3)

1.1 The mass of oxygen used up in this reaction is 6,4 g, as oxygen is the limiting reagent in this reaction.To determine the mass of H_2O produced:

- Convert the mass of O_2 to **moles.**
- Compare the mole ratio in which O_2 gets used up in the reaction, to the mole ratio in which H_2O is produced, to determine the number of moles of H_2O produced.
- Convert the number of moles of H_2O produced to mass using the formula: $n = \frac{m}{M}$

1.1 n(O_2 used up) = $\frac{m}{M}$
n(O_2 used up) = $\frac{(6,4)}{(32)}$
n(O_2 used up) = 0,2 mol

$M(O_2) = 2(16)$
$M(O_2) = 32\ g.mol^{-1}$

n(O_2 used up) : n(H_2O produced)
1 : 2
0,2 mol : 0,4 mol

n(H_2O produced) = $\frac{m}{M}$
(0,4) = $\frac{m}{(18)}$
m(H_2O produced) = (0,4)(18)
m(H_2O produced) = 7,20 g

$M(H_2O) = 2(1)+16$
$M(H_2O) = 18\ g.mol^{-1}$

PRO - TIPS

Limiting reagent: Reactant that is completely used up or reactant that is used up first and limits the other reactant from completely reacting.

Reactant in excess: Reactant that is left over at the end of the reaction.

The reactant in excess ensures that all of the other reactant gets completely used up.

1.2 The number of moles of O_2 used up and H_2O produced is known. Using the mole ratios from the balanced chemical reaction, the number of moles of H_2(g) used up can be determined, and this can be used to determine the volume of H_2 (g) used up, using the formula: $n = \frac{V}{V_m}$

1.2 n(O_2 used up) . n(H_2 used up)
1 : 2
0,2 mol : 0,4 mol

n(H_2 used up) = $\frac{V}{V_m}$
(0,4) = $\frac{V}{(22,4)}$
V(H_2 used up) = (0,4)(22,4)
V(H_2 used up) = 8,96 dm^3

NOTE: Only the final answer in a calculation is rounded off to two decimal places.

Worked examples

1. Initially the concentration of the reactant hydrochloric acid in a reaction vessel was 0,1 mol.dm^{-3}. After 3 minutes it has decreased to 0,04 mol.dm^{-3}. Calculate the average rate of the reaction (in mol.dm^{-3}.s^{-1}).

Check the units in which the average rate needs to be represented in: mol.dm^{-3}.s^{-1}. This means that the rate of the reaction is being calculated by looking at how the **concentration** of the hydrochloric acid **reactant** changes with time.

The given time is 3 minutes, this must be converted to seconds, by x 60.

$\triangle t = 3 \times 60 = 180$ s.

$$\text{Rate} = -\left(\frac{\Delta c}{\Delta t}\right)$$

$$\text{Rate} = -\left(\frac{c_f - c_i}{t_f - t_i}\right)$$

$$\text{Rate} = -\left(\frac{(0{,}04)-(0{,}1)}{(180)-(0)}\right)$$

$$\text{Rate} = 3{,}33 \times 10^{-4}\ \text{mol.dm}^{-3}.\text{s}^{-1}$$

PRO-TIPS

Time conversion chart:

min → s x 60
hours → s x 3600

OR

s → min ÷ 60
s → hours ÷ 3600

2. Consider the following chemical reaction:

$$3H_2(g) + N_2(g) \rightarrow 2NH_3(g)$$

0,4 g of H_2 is reacted in the above reaction. After 2 minutes 0,2 g of H_2 is left over. Calculate the average rate of reaction in mol.min^{-1} after 2 minutes.

OPTION 1

Check the units in which the average rate needs to be represented in the question: mol.min^{-1}. This means that the rate of the reaction is being calculated by looking at how the number of moles of the H_2(g) **reactant** changes with time. The initial and final mass of H_2 is given, this must be converted into moles, so that the rate can be calculated in mol.min^{-1}. The given time is 2 minutes.

$M(H_2) = 2(1)$
$M(H_2) = 2$ g.mol^{-1}

$$n(H_2\ \text{initial}) = \frac{m}{M}$$

$$n(H_2\ \text{initial}) = \frac{(0{,}4)}{(2)}$$

$$n(H_2\ \text{initial}) = 0{,}2\ \text{mol}$$

$$n(H_2\ \text{final}) = \frac{m}{M}$$

$$n(H_2\ \text{final}) = \frac{(0{,}2)}{(2)}$$

$$n(H_2\ \text{final}) = 0{,}1\ \text{mol}$$

$$\text{Rate} = -\left(\frac{\Delta n}{\Delta t}\right)$$

$$\text{Rate} = -\left(\frac{n_f - n_i}{t_f - t_i}\right)$$

$$\text{Rate} = -\left(\frac{(0{,}1)-(0{,}2)}{(2)-(0)}\right)$$

$$\text{Rate} = 0{,}05\ \text{mol.min}^{-1}$$

→ 0,05 mol of H_2(g) is used up per minute

OPTION 2

Check the units in which the average rate needs to be represented in the question: mol.min^{-1}. This means that the rate of the reaction is being calculated by looking at how the number of moles of the H_2(g) **reactant** changes with time. The initial and final mass of H_2 is given, this can be used calculate the mass of H_2 used up in 2 minutes (the change in mass of H_2). The rate of the reaction can be calculated in mol.min^{-1}. The given time is 2 minutes.

m(H_2 used up) = 0,4 – 0,2
m(H_2 used up) = 0,2 g

n(H_2 used up) = $\frac{m}{M}$
n(H_2 used up) = $\frac{(0,2)}{(2)}$
n(H_2 used up) = 0,1 mol

M(H_2) = 2(1)
M(H_2) = 2 g.mol^{-1}

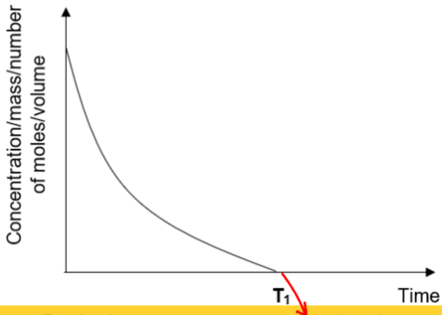
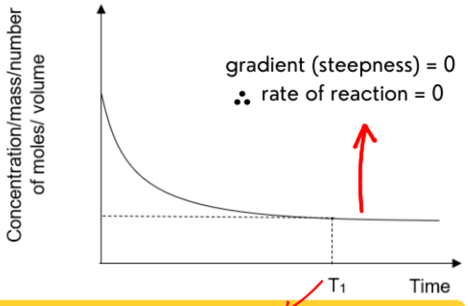
Rate = $\left(\frac{\Delta n}{\Delta t}\right)$
Rate = $\left(\frac{0,1}{2}\right)$
Rate = 0,05 mol.min^{-1} → 0,05 mol of H_2(g) is used up per minute

REACTION RATES & GRAPHS

Reactants

In a chemical reaction that reaches completion (stops), there is usually a **limiting reagent** and a **reactant that is in excess.**

A rate graph, representing how the concentration or mass or volume (of a gas) or number of moles of a reactant changes with time, can be sketched:

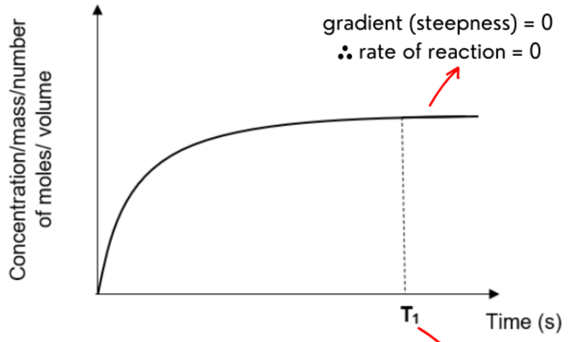
LIMITING REAGENT (reactant completely used up)	**REACTANT IN EXCESS** (reactant left over at the end of the reaction)
Concentration/mass/number of moles/volume – time graph for a reactant that is the limiting reagent:  At time T_1 ,the limiting reagent is completely used up and the **reaction reaches completion.**	**Concentration/mass/number of moles/volume – time graph for a reactant in excess:**  At time T_1 ,the limiting reagent is completely used up and the **reaction reaches completion.** There is still of the reactant in excess left over.
• At the start of the reaction, concentration/mass/volume/number of moles of a reactant is high. • As the reaction proceeds the concentration of the reactant decreases since the reactant is being used up. • Gradient= $\frac{\Delta c}{\Delta t}$ OR $\frac{\Delta n}{\Delta t}$ OR $\frac{\Delta m}{\Delta t}$ OR $\frac{\Delta V}{\Delta t}$ The gradient represents the **AVERAGE rate of the reaction.** • As the reaction proceeds the **STEEPNESS** of the graph **DECREASES**, therefore the rate of the reaction decreases, since the reactant is being used up.	• At the start of the reaction, concentration/mass/volume/number of moles of a reactant is high. • As the reaction proceeds the concentration of the reactant decreases since the reactant is being used up. • Gradient= $\frac{\Delta c}{\Delta t}$ OR $\frac{\Delta n}{\Delta t}$ OR $\frac{\Delta m}{\Delta t}$ OR $\frac{\Delta V}{\Delta t}$ The gradient represents the **AVERAGE rate of the reaction.** • As the reaction proceeds the **STEEPNESS** of the graph **DECREASES**, therefore the rate of the reaction decreases, since the reactant is being used up.

Products

In a chemical reaction, as the reactant/s get used up, products are formed. The concentration or mass or volume (of a gas) or number of moles of a product increases with time. This can be represented on a rate graph:

PRODUCT

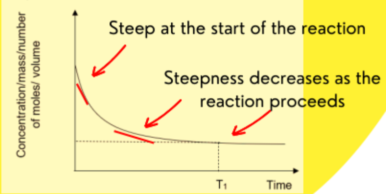
Concentration/mass/number of moles/ volume – time graph for a product



At time T_1 ,the limiting reagent is completely used up and the **reaction reaches completion. No more product is produced and the mass/concentration/number of moles/ volume of product remains constant.**

PRO-TIPS

Draw a tangent to the curve (a line that touches the graph at one point only) to determine how the rate of the reaction changes as the reaction proceeds:



- At the start of the reaction (T = 0) initially there is no product formed. As the reaction proceeds, the concentration of the product increases since the product is being formed.
- Gradient = $\frac{\Delta c}{\Delta t}$ **OR** $\frac{\Delta n}{\Delta t}$ **OR** $\frac{\Delta m}{\Delta t}$ **OR** $\frac{\Delta V}{\Delta t}$

  The gradient represents the average rate of the reaction.
- As the reaction proceeds the **STEEPNESS** of the graph **DECREASES**, therefore the rate of the reaction decreases.
- At time T_1 the reaction reaches completion (i.e. the reaction stops because the limiting reagent is completely used up), and the concentration of the product remains constant as no more product is produced.

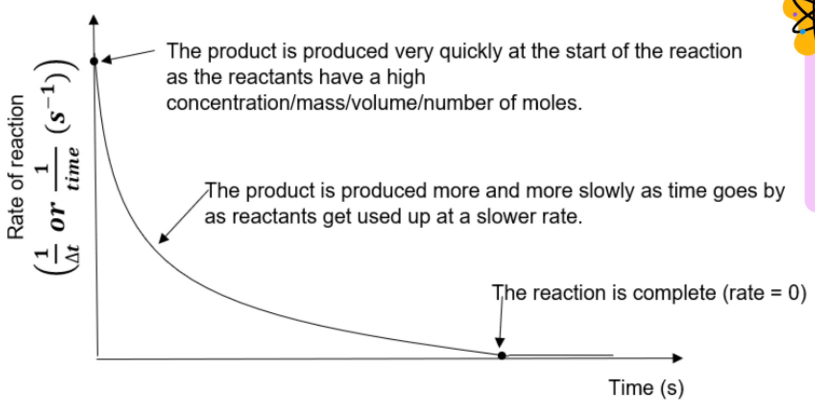
PRO-TIPS

Stoichiometric calculations can be applied to the graph questions.

Reaction- rate time graph

The reaction - rate time graph represents how the rate of a chemical reaction changes with time:

RATE OF REACTION $(\frac{1}{\Delta t})$– TIME GRAPH



NOTE: The rate of reaction - time graph is not a linear graph, as the reaction rate is not constant, it changes with time.

Worked example

C + A

Multiple choice question

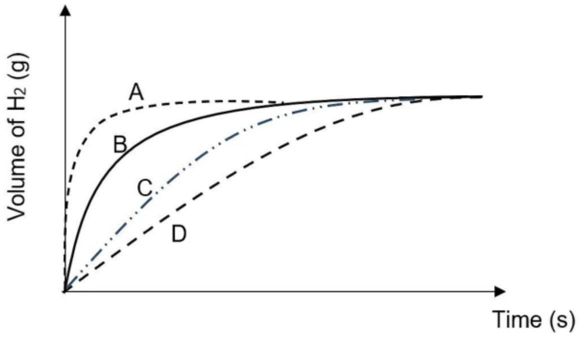
Zinc reacts with hydrochloric acid, according to the following balanced reaction:

$$Zn\ (s) + 2HCl\ (aq) \longrightarrow ZnCl_2\ (aq) + H_2\ (g)$$

Four experiments (**1** – **4**) are conducted. The conditions are represented in the table below.

Experiment	**Concentration of $HC\ell$ (aq)**	**Volume of $HC\ell$ (aq)**	**Temperature**	**State of subdivision of Zn**
1	0,5 mol.dm^{-3}	100 cm^3	30°C	powder
2	0,5 mol.dm^{-3}	100 cm^3	30°C	chunks
3	0,7 mol.dm^{-3}	100 cm^3	30°C	powder
4	0,7 mol.dm^{-3}	100 cm^3	40°C	powder

The volume of H_2 (g) collected versus time graph for experiment **1** – **4** is represented in graph **A** - **D** below.



Which ONE of the following graphs represents experiment **1** – **4**:

A	Graph **A**: Experiment **1** Graph **B**: Experiment **2** Graph **C**: Experiment **3** Graph **D**: Experiment **4**
B	Graph **A**: Experiment **4** Graph **B**: Experiment **3** Graph **C**: Experiment **2** Graph **D**: Experiment **1**
C	Graph **A**: Experiment **4** Graph **B**: Experiment **3** Graph **C**: Experiment **1** Graph **D**: Experiment **2**
D	Graph **A**: Experiment **3** Graph **B**: Experiment **4** Graph **C**: Experiment **1** Graph **D**: Experiment **2**

Answer: C

Analyse the steepness of each of the graphs:

Graph **A**: Steepest graph, reaction reaches completion in the shortest period of time.

Graph **B**: less steep than graph A, but steeper than graph C and D, therefore it represents a slower reaction rate than graph A, but a faster reaction rate than graph C and D.

Graph **C**: Less steep than graph A and B, but more steep than graph D. Therefore it represents a slower reaction rate than graph A and B, but faster reaction rate than graph D.

Graph **D**: Least steep graph, therefore, it represents the slowest reaction rate.

Match the graphs to the experiments:

- Considering the reaction conditions for experiment 1 - 4, the concentration of the HCl solution in experiment 3 and 4 is the highest and in both experiment 3 and 4 and Zn powder is used. Therefore, experiment 3 and 4 will have the faster reaction rates, compared to experiment 1 and 2. However, experiment 4 is taking place at a higher temperature than experiment 3 (and experiment 1 and 2), therefore it has the fastest reaction rate, which is represented by the steepest graph, graph **A.**
- Graph B represents the reaction with the second fastest reaction rate, this is experiment 3.

- Experiment 1 and 2 have similar reaction conditions, but because experiment 1 uses Zn powder, and experiment 2 uses Zn chunks, experiment 1 takes place at a **faster reaction rate** than experiment 2, therefore experiment 1 is represented by graph C and experiment 2 represented by graph D.

Worked example

A + P

A group of learners use the reaction between EXCESS hydrochloric acid and magnesium powder to investigate one of the factors that influence the rate of a chemical reaction. The reaction that takes place is:

$$Mg(s) + 2HC\ell\,(aq) \rightarrow MgC\ell_2\,(aq) + H_2(g)$$

The learners use the apparatus and follow the method shown below to conduct the investigation.

PRO-TIPS

The introduction and method of the experiment can be used to determine the independent variable and dependent variable in the experiment.

Method – Experiment 1:

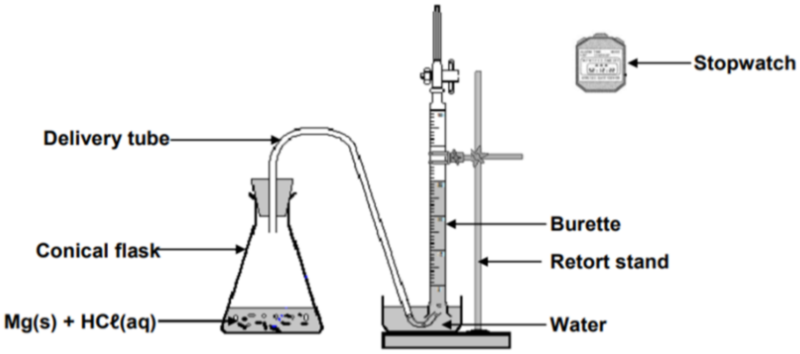
Step 1: Place a spatula of magnesium powder in a conical flask and add 50 cm^3 $HC\ell(aq)$ with a concentration of 0,15 $mol.dm^{-3}$.

Step 2: Simultaneously start the stopwatch and close the flask with the rubber stopper containing the delivery tube.

Step 3: Measure the volume of the $H_2(g)$ formed in time intervals of 20 seconds.

Method – Experiment 2:

Repeat steps 1 to 3 above, but use only 25 cm^3 of the same $HC\ell(aq)$ diluted to 50 cm^3 with distilled water.



1.1 Write down the:

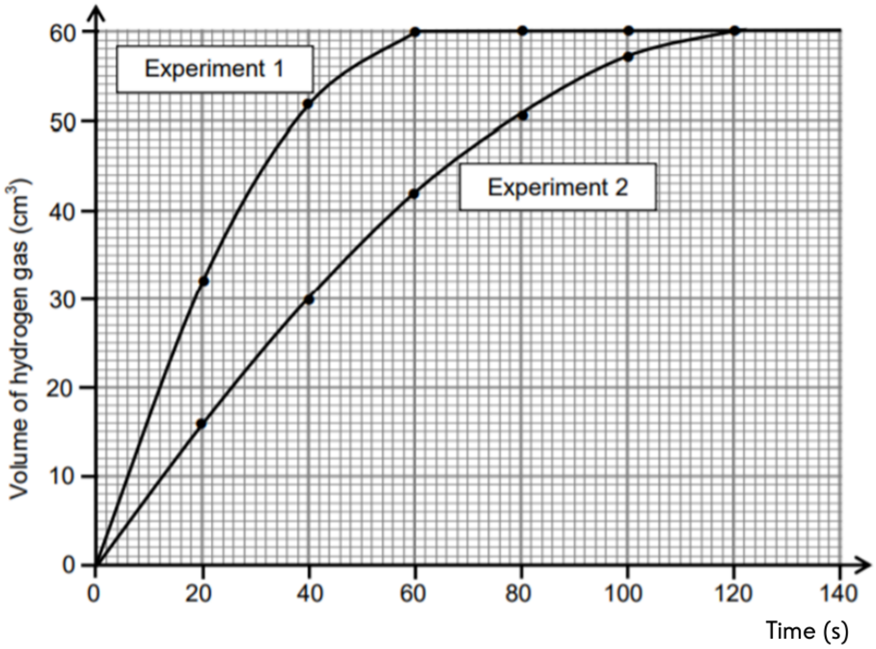
1.1.1 Dependent variable (1)

1.1.2 Independent variable (1)

1.2 Write down an investigative question for this investigation. (2)

1.3 Calculate the concentration of the acid in Experiment **2**. (4)

After completing the investigation, the learners represent the results obtained during each experiment in the graph below:



1.4 Calculate the average reaction rate for Experiment **1** between 20 and 40 s in dm^3.s^{-1}. (4)

1.5 Which one of the experiments (experiment **1** or experiment **2**) took place at the faster rate? Refer to the shape of the curves to motivate your answer. (2)

1.6 What conclusion can the learners draw from their results obtained? (2)

1.7 Give a reason why the final volume of gas produced is the same in both experiments. (2)

1.8 How will an increase in the temperature influence the following:

1.8.1 Final volume of gas obtained in each experiment. (Write down only INCREASES, DECREASES or REMAINS THE SAME). (1)

1.8.2 Volume of gas obtained in each experiment after 40 s. (Write down only INCREASES, DECREASES or REMAINS THE SAME.) (1)

1.10 Calculate the initial mass of magnesium. The reaction took place at STP. (5)

NOTE: Factors kept constant in experiment 1 and 2:

- surface area of Mg solid
- Mass of Mg solid
- Temperatiure
- Pressure of gases.

These are all the other factors that affect the rate of a chemical reaction.

1.1.1 The dependent variable is the variable being measured in the experiment. In this experiment, the volume of H_2(g) produced is being determined, to measure **the RATE of the chemical reaction.**

1.1.2 The independent variable is the variable that is being deliberately changed or manipulated. Compare experiment 1 and 2: What VARIABLE is being changed? By diluting the solution, the CONCENTRATION of the solution is being changed. Independent variable: Concentration of the solution.

1.2 An investigative question is a question about what is being investigated. The introduction explaining the experiment gives a good indication of what is being investigated.
The investigative question must include the independent variable, dependent variable and a question mark.

PRO-TIPS

A mark will be lost if the investigative question does not have a question mark at the end.

How does the concentration (of a solution) affect the rate of a chemical reaction**?**

OR

What is the relationship between the concentration (of a solution) and the rate of a chemical reaction**?**

1.3

In experiment 2, only a portion of the volume of HCl is used. The concentration of this portion is still 0,15 mol.dm^{-3} . However, when 25 cm^3 of water is added to the portion of HCl solution, this increases the volume of solvent (however, the number of moles of solute remains constant), therefore the concentration of the solution **decreases,** since $c \propto \frac{1}{V}$ (concentration is inversely proportional to the volume of solvent) provided n remains constant. The number of moles of solute remains constant.

OPTION 1 **OR** **OPTION 2**

OPTION 1

c (25 cm^3 HCl solution) = $\frac{n}{V}$

(0,15) = $\frac{n}{(0{,}025)}$

n(25 cm^3 HCl solution) = 3,75 x 10^{-3} mol

n(25 cm^3 HCl solution) = n (50 cm^3 diluted HCl solution)

c(50 cm^3 diluted HCl solution) = $\frac{n}{V}$

c(50 cm^3 diluted HCl solution) = $\frac{(3{,}75 \times 10^{-3})}{(0{,}05)}$

c(50 cm^3 diluted HCl solution) = 0,075 mol.dm^{-3}

OPTION 2

n(25 cm^3 HCl concentrated solution) = n(50 cm^3 HCl diluted solution)

$c_1V_1 = c_2V_2$ → **Dilution formula**

$(0{,}15)(0{,}025) = c_2(0{,}05)$

$c_2 = \frac{(0{,}15)(0{,}025)}{(0{,}05)}$

c_2 = 0,075 mol.dm^{-3}

1.4 To calculate the average rate of the reaction for experiment 1 between 20 s and 40 s, a line can be drawn from 20 s to 40 s. The gradient of the line can be calculated (gradient = $\frac{\Delta V}{\Delta t}$), and this represents the average rate of the reaction between 20 s and 40 s.

OPTION 1

Gradient = $\frac{\Delta y}{\Delta x} = \frac{\Delta V}{\Delta t}$ = rate

Rate = $\frac{\Delta V}{\Delta t}$

Rate = $\frac{(52)-(32)}{(40)-(20)}$

Rate = 1 cm^3.s^{-1}

OR

OPTION 2

Gradient = $\frac{\Delta y}{\Delta x}$

Gradient = $\frac{(52)-(32)}{(40)-(20)}$

Gradient = 1

$\therefore$ Rate = 1cm^3.s^{-1}

1.5 To determine which reaction takes place at a faster rate:

- the steepness of the curves must be compared.
- the time taken for the reactions to reach completion must be compared.

Experiment 1. Experiment 1 is represented by a steeper curve than experiment 2 and experiment 1 reaches completion before experiment 2.

1.6 The conclusion of the investigation must link up to the aim and the investigative question for this experiment, and is the answer to the investigative question: How does the concentration (of a solution) affect the rate of a chemical reaction?

Conclusion: The greater (higher) the concentration of a solution, the faster the reaction rate.

OR

The lower the concentration of a solution, the slower the reaction rate.

1.7 Mg is the limiting reagent in this experiment **1** and **2**, therefore if the mass of Mg used up in experiment 1 and 2 is the same, therefore, the same mass of $H_2(g)$ will be produced at the end of the reaction.

∴The same mass of Mg (magnesium) is used in experiment 1 and 2, therefore, the same volume of $H_2(g)$ is produced.

1.8 According to the collision theory:

- Increasing the temperature of a substance increases the average kinetic energy of the particles.
- More particles will now have a sufficient amount of kinetic energy ($E_k \geq E_a$) to react.
- The number of effective collisions per unit time increases and the rate of the reaction increases.

1.8.1 Increasing the temperature increases the reaction rate, but it does NOT affect the TOTAL volume of $H_2(g)$ produced at the end of the reaction, only the rate at which it is produced. Therefore at the end of the reaction, the same **TOTAL/FINAL** volume of $H_2(g)$ is produced, in a shorter period of time.

∴Remains the same.

1.8.2 Increasing the temperature increases the reaction rate, therefore it affects the rate at which H_2 is produced, and therefore, the amount of H_2 produced per second. After 40 s, a greater volume of $H_2(g)$ would be produced in that time period, due to the increased reaction rate.

∴ Increases.

1.9 Mg is the limiting reagent in this reaction, therefore all the Mg was used up and the initial mass of Mg is therefore the mass of Mg used up in the reaction.

To determine the mass of Mg used up, and therefore the initial mass of Mg:

- the volume of $H_2(g)$ collected at the end of the reaction at STP is converted to moles.
- Using mole ratios from the balanced reaction, the number of moles of Mg used up can be determined.
- The mass of Mg used up can be determined, by converting the number of moles of Mg used up to mass of Mg used up, using the formula: $n = \frac{m}{M}$
  This mass is equal to the initial mass of Mg.

From the graph

n (H_2 produced) = 60 cm^3 = 0,06 dm^3

n (H_2 produced) = $\frac{V}{V_m}$

n (H_2 produced) = $\frac{(0{,}06)}{(22{,}4)}$

n (H_2 produced) = 2,678... x 10^{-3} mol

n(Mg used up) : n (H_2 produced)
1 : 1

n (Mg used up) = n(H_2 produced) = 2,678... x 10^{-3} mol

n(Mg used up) = $\frac{m}{M}$

2,678... x 10^{-3} = $\frac{m}{(24)}$

m(Mg used up) = (2,678... x 10^{-3})(24)

m(Mg used up) = 0,064 g

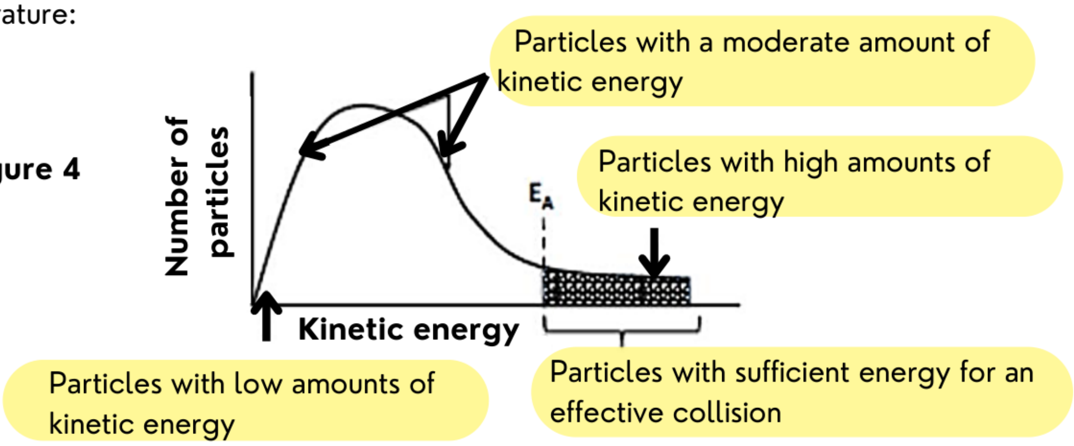
initial mass of Mg = 0,064 g

MAXWELL-BOLTZMANN DISTRIBUTION CURVES

The Maxwell-Boltzmann distribution curve is a graph that shows how the kinetic energy of the particles in a substance is distributed.

Figure 4 represents a Maxwell - Boltzmann distribution curve for a substance at a moderate temperature:

Figure 4



Conclusions drawn from the Maxwell Boltzmann distribution curve representing a substance at a moderate temperature:

1. Most particles have a moderate amount of kinetic energy.
2. Very few particles have high amounts of kinetic energy.
3. Very few particles have very low amounts of kinetic energy.
4. No particles have no kinetic energy.

The shaded area represents the number of particles with energy equal to or greater than the activation energy ($E_k \geq E_a$) to collide effectively.

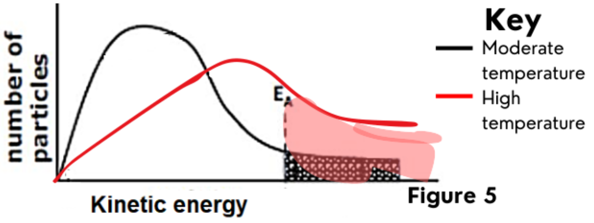
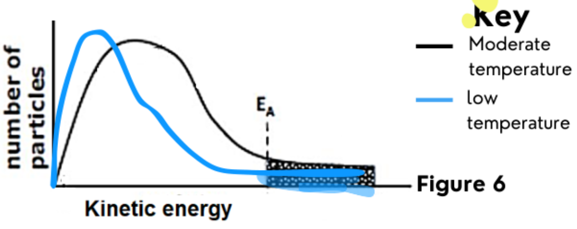
- Very few particles have enough kinetic energy to react.

Maxwell Boltzmann distribution curve: Factors affecting the reaction rate

1. Temperature

PRO-TIPS

The graph always starts at the origin, as there are no particles with no kinetic energy.

HIGH TEMPERATURE	LOW TEMPERATURE
 Figure 5	 Figure 6
• Increasing the temperature 'shifts' the curve to the right and the curve "flattens", as more particles have a higher kinetic energy. The area under the curve remains constant because the number of particles remains constant due to the concentration remaining constant. • More particles to have a sufficient amount of kinetic energy to react ($E_k \geq E_a$). This is represented by the red shaded region in **figure 5** above.	• Decreasing the temperature 'shifts' the curve to the left and the curve "peaks" to the left, as more particles have a **lower** kinetic energy. The area under the curve remains constant because the number of particles remains constant due to the concentration remaining constant. • Fewer particles have a sufficient amount of kinetic energy to react ($E_k \geq E_a$) . This is represented by the blue shaded region in **figure 6** above.

2.Addition of a catalyst

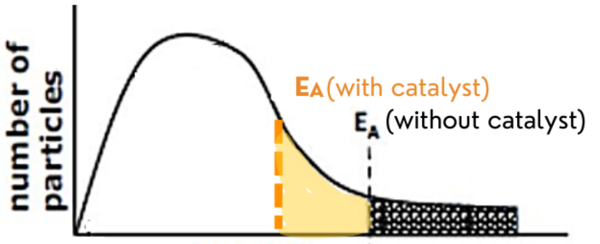
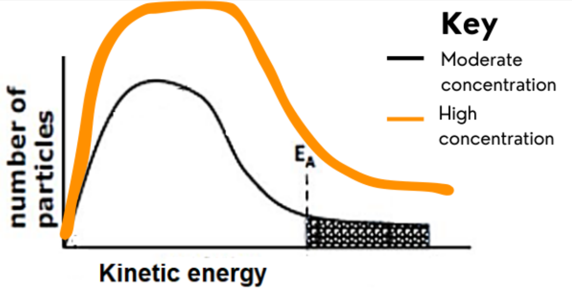
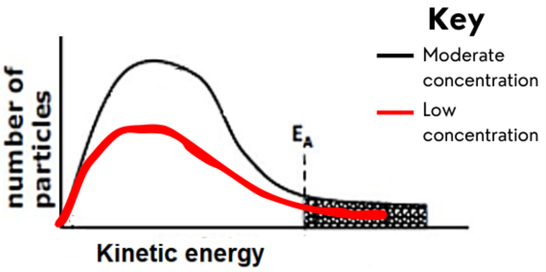


Figure 7

- The shape of the curve remains the same (i.e. it does not change/shift).
- The activation energy is **lowered** (see orange dotted line in **figure 7** above), allowing more particles to have a sufficient amount of kinetic energy to react.

NOTE: Adding a catalyst does **not** change the average kinetic energy of the particles.

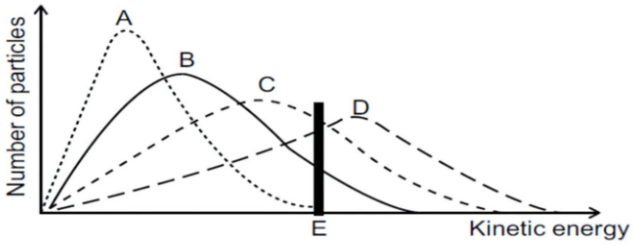
3.Concentration (of solutions)

HIGH CONCENTRATION	LOW CONCENTRATION
 • The greater the concentration of the solution, the greater the number of particles (in the solution) • the greater the area under the curve.	 • The lower the concentration of the solution, the fewer the number of particles (in the solution) • the smaller the area under the curve.

Worked example

Multiple choice questions

1. The Maxwell-Boltzmann energy distribution curves below show the number of particles as a function of their kinetic energy for a reaction at four different temperatures. The minimum kinetic energy needed for effective collisions to take place is represented by **E**.

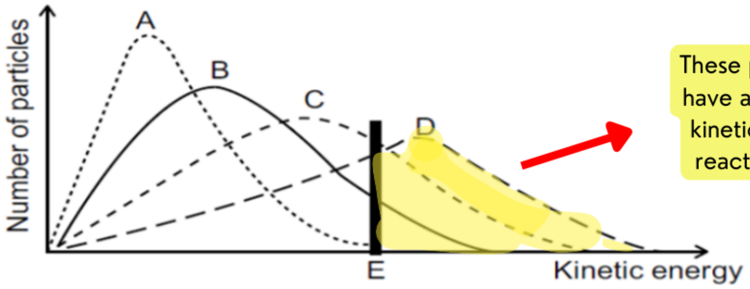


Which ONE of these curves represents the reaction with the slowest reaction rate?

A A
B B
C C
D D

Answer: A

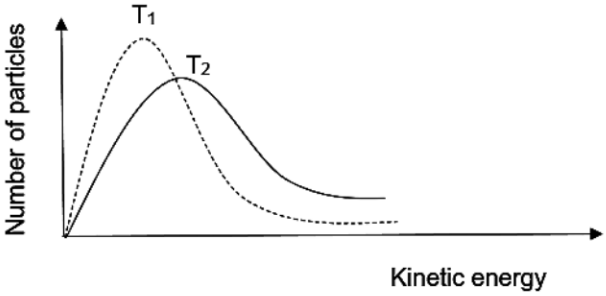
E represents the activation energy, which is the minimum energy needed for the reaction to take place. Particles that have a kinetic energy greater than or equal to the activation energy will react, these are the particles to the right of **E** in the diagram.



These particles highlighted have a sufficient amount of kinetic energy to react in reaction **A, B, C** and **D**.

Diagram **A** represents a reaction where the fewest amount of particles have a sufficient amount of kinetic energy to react, therefore it has the slowest reaction rate, as there will be fewer effective collisions compared to reaction **B**, **C** and **D**.

2. The Maxwell- Boltzmann distribution curves for the same volume of gas at two different temperatures, T_1 and T_2 are shown below.



Which ONE of the following is the correct interpretation of the diagrams as the temperature of the gases changes from T_1 to T_2 ?

	Activation energy (E_a)	Number of effective collisions
A	Remains the same	Increases
B	Decreases	Decreases
C	Decreases	Increases
D	Remains the same	Decreases

Answer: A

Activation energy

Only the addition of a catalyst can change the activation energy i.e., decrease the activation energy. Therefore with any change in temperature, the **activation energy remains the same**.

Number of effective collisions

The change in temperature from T_1 to T_2 is an **increase in temperature.**

The peak of the curve flattens and the graph shifts to the right, indicating that more particles having a sufficient amount of kinetic energy to react, therefore the number of effective collisions (per unit time) increases with an increase in temperature.

CHEMICAL EQUILIBRIUM $\rightleftharpoons$

Introduction

- In many chemical reactions covered to date, the reactants have been completely transformed into product molecules. The reaction is said to reach completion (i.e., stop) when one of the reactants is completely used up. Reactions that go to completion are irreversible.
- However, **not all reactions reach completion**. In some reactions, the reactants form products (in the forward reaction), and the products can be converted back into reactants (in the reverse reaction).
  This type of reaction is said to have reached equilibrium.
- We think of equilibrium as a 'balance' or 'equal' therefore when a chemical reaction reaches equilibrium (dynamic chemical equilibrium), the rate of the forward reaction is equal to the rate of the reverse reaction.

A reaction can only reach dynamic chemical equilibrium if the following two conditions are met:

1. the reaction is a reversible reaction
2. the system is a closed system.

$\rightleftharpoons$ 1.What is a reversible reaction?

Reversible reaction: A reaction where products can be converted back to reactants.

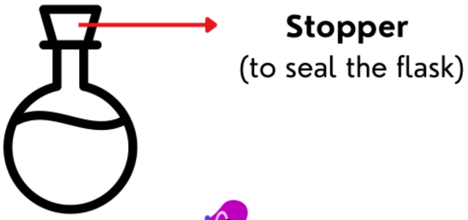
A reversible reaction is indicated using double arrows, representing the forward and the reverse reaction: $\rightleftharpoons$

Example: $A + B \rightleftharpoons C + D$

$\rightleftharpoons$ 2.What is a closed system?

Closed system: A closed system is isolated from its surroundings.

An example of a closed system a sealed flask or a sealed vessel:



PRO-TIPS

In **chemistry (paper 2)** it is called a closed system and in **physics (paper 1)** it is referred to as an isolated system. The two concepts cannot be switch around.

NOTE: A closed system is a system that only exchanges energy with its surroundings, but it does not exchange matter with its surroundings.

What is chemical equilibrium?

Definition: Chemical equilibrium: is a dynamic equilibrium when the rate of the forward reaction equals the rate of the reverse reaction.

When a reaction reaches equilibrium, the rate at which reactants are reacting to form products, is the same rate at which products are being converted back into reactants, hence the rate of the forward reaction equals the rate of the reverse reaction.
When a chemical reaction reaches equilibrium, it appears as though nothing is happening in the closed system!

NOTE: When a chemical reaction reaches equilibrium, the following factors remain constant:

1. Concentration of all solutions and gases.
2. Temperature
3. Pressure of a gaseous system

NOTE:
- **Only** the concentration of aqueous solutions and gases can change.
- The concentration of a **solid** and a **pure liquid cannot** change and always remains constant.

NOTE: A system is a **gaseous system** if **at least one** of the reactants **or** products is a gas.

Le Chatelier's principle: Factors that affect the equilibrium of a system

If a system is in equilibrium, the equilibrium of the system can be affected by:

1. A **change** in temperature
2. A **change** in concentration [of a solution (aq) or gas (g)]
3. A **change** in pressure (gaseous systems only & if the gaseous system can respond to a change in pressure)

C P T

PRO-TIPS

The acronym CPT can be used to remember which factors affect the equilibrium of a system.

The above factors (physical quantities) **remain constant at equilibrium.** Therefore, if one of the factors is changed, the rate of the forward and reverse reaction changes and is no longer equal, therefore the equilibrium of the system gets disturbed.
Henry Le Chatelier discovered how to manipulate the equilibria in industry:

Definition: **Le Chatelier's principle**: states that when the equilibrium in a closed system is disturbed, the system will re-instate a new equilibrium by favouring the reaction that will oppose the disturbance.

Le Chatelier's principle explained: !!

NOTE: The **use of a catalyst does not affect the equilibrium of a system**. This will be explained later in the chapter.

Key words from the definition:
"**Disturb**": by changing a reaction condition/ factor.
"**Favouring the reaction**": a reaction taking place at a faster rate.

For example:

"**favours the forward reaction**": favours **reactants** → **products** (favours the production of products, i.e., there will be more product being produced per second).
"**favours the reverse reaction**": favours **products** → **reactants** (favours the production of reactants, i.e., there will be more reactants being produced per second).

How does the system respond to the disturbance of the equilibrium of the system?

The system tries to restore the equilibrium by counteracting (or opposing) the change, and it does so by favouring the reaction that opposes the disturbance i.e., it causes the reaction (forward or reverse) that **counteracts the change, to take place at a faster rate**.

1. Using Le Chatelier's principle to explain the effect of a change in concentration (of a gas or a solution) on equilibrium.

Consider the following hypothetical reaction that has reached equilibrium:

$$A\,(g) + B\,(g) \rightleftharpoons C(g)$$

The concentration of a reactant (g) or (aq) is increased.

- According to Le Chatelier's principle, if the concentration of a reactant is increased, the system will respond to counteract the change by favouring the reaction that decreases the concentration of the reactant **i.e., by favouring the reaction that uses up some of the reactant** (to decrease its concentration).
- The forward reaction will be favoured to use up some of the reactant.

The concentration of a reactant (g) or (aq) is decreased.

- According to Le Chatelier's principle, if the concentration of a reactant is decreased, the system will respond to counteract the change by favouring the reaction that increases the concentration of the reactant **i.e., by favouring the reaction that produces more of the reactant** (to increase its concentration).
- The reverse reaction will be favoured to produce more of the reactant.

The concentration of a product (g) or (aq) is increased.

- According to Le Chatelier's principle, if the concentration of a product is increased, the system will respond to counteract the change by favouring the reaction that decreases the concentration of the product **i.e., by favouring the reaction that uses up some of the product** (to decrease its concentration).
- The reverse reaction will be favoured to use up some of the product.

The concentration of a product (g) or (aq) is decreased.

- According to Le Chatelier's principle, if the concentration of a product is decreased, the system will respond to counteract the change by favouring the reaction that increases the concentration of the product **i.e., by favouring the reaction that produces some of the product** (to increase its concentration).
- The forward reaction will be favoured to produce some of the product.

How to increase or decrease the concentration of a gas (g)

- Adding more gas will increase the number of moles of gas and therefore increase the concentration of the gas.
- Removing some of the gas will decrease the number of moles of gas and therefore decrease the concentration of the gas.

How to increase the concentration of a solution (aq)

- Increase the mass of solute, therefore increasing the number of moles of solute.
- Evaporate some of the solvent. When some of the solvent is evaporated, the concentration of the solution increases.

How to decrease the concentration of a solution (aq)

- Increasing the volume of solvent (e.g. water).
  Increasing the volume of the solvent decreases the concentration of the solution, and dilutes the solution.
- Decreasing the mass of solute.

Worked example

C + A

1. Consider the reaction between sulphur dioxide and oxygen to produce sulphur trioxide, at equilibrium:

$$2SO_2\,(g) + O_2\,(g) \rightleftharpoons 2SO_3\,(g)$$

1.1 Explain what the effect the following changes would have on the concentration of $SO_3(g)$:

1.1.1 Increasing the amount of SO_2. (4)

1.1.2 Decreasing the amount of O_2 in the container. (4)

Tips for explaining answers using Le Chatelier's Principle:

1. **State** the **factor** being changed (i.e., a change in concentration/temperature/pressure of a gaseous system).
2. **Use** Le Chatelier's **principle** to determine how the system will respond to counteract the change.
3. **Determine reaction** (forward or reverse) will favoured (i.e. take place at a faster rate).
4. **Draw** a **conclusion** (based on the question asked).

1.1.1

- Increasing the amount of $SO_2(g)$ increases the concentration of the $SO_2(g)$.
- According to Le Chatelier's principle when the concentration of the SO_2 reactant is increased, the system will respond to counteract the change by favouring the reaction that decreases the concentration of SO_2 (g), i.e., the reaction that uses up some of the SO_2 (g).
- In this reaction the forward reaction will be favoured (as this is the reaction that will uses up the $SO_2(g)$.
- Therefore, the concentration of SO_3 (g) increases.

PRO-TIPS

Answer explanation questions using bullet points - it makes it much easier for the marker to read.

1.1.2

- Decreasing the amount of O_2 (g) decreases the concentration of the $O_2(g)$.
- According to Le Chatelier's principle when the concentration of the $O_2(g)$ reactant is decreased, the system will respond to counteract the change by favouring the reaction that increases the concentration of O_2 (g), i.e., the reaction that produces O_2 (g).
- In this reaction the reverse reaction will be favoured (as this is the reaction that produces the O_2 (g).
- Therefore, the concentration of SO_3 (g) decreases.

The common ion effect

Example:

A saturated solution of NaCl is prepared. When NaCl (an ionic compound) dissolves in water, it dissociates (separates) into its component ions according to the following equation:

$$NaCl\ (s) \overset{H_2O}{\rightleftharpoons} Na^+\ (aq) + Cl^-\ (aq)$$

Reversible process that can reach equilibrium

The following ions are in solution: Na^+ and Cl^- ions

Disturbance to the equilibrium: Concentrated hydrochloric acid (HCl) is added to the saturated NaCl solution:

Identify the ion that HCl and NaCl have in **common**: Cl^- ions

Therefore the addition of concentrated HCl (aq) **increases the concentration** of Cl^- ions in solution.The common ion effect is therefore an **example of a change in concentration at equilibrium.**

Le Chatelier's principle can be used to explain how the system will respond:

- When HCl is added to the saturated solution of NaCl, the addition of Cl^- ions increases the concentration of Cl^- ions in solution.
- According to Le Chatelier's principle, the system will respond to counteract the change by favouring the reaction that decreases the concentration of Cl^- ions in solution i.e., the reaction that uses up the Cl^- ions.
- In this reaction, the reverse reaction uses up the Cl^- ions and is therefore favoured.
- The concentration of Cl^- ions in solution decreases.

Worked example

Multiple choice question

The following system is in equilibrium.

$$\underset{\text{Blue}}{CoCl_4^{2-}}\ (aq) + 6H_2O\ (l) \rightleftharpoons \underset{\text{Pink}}{[Co(H_2O)_6]^{2+}}\ (aq) + 4Cl^-\ (aq)$$

NaCl (aq) solution is now added to the equilibrium mixture. Which ONE of the following represents the effect on the concentration of H_2O (l) and the colour of the solution observed.

	Concentration of H_2O	Colour of solution observed
A	Increases	Blue
B	Decreases	Pink
C	Remains the same	Blue
D	Remains the same	Pink

Answer: C

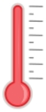
Concentration of H_2O

H_2O is a **pure liquid**, therefore its concentration cannot change.

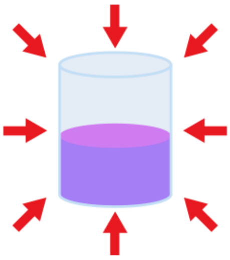
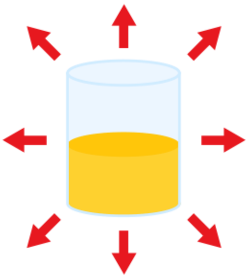
Colour of solution observed

NaCl (aq) contains Na^+ and Cl^- ions in solution. When NaCl is added to the equilibrium mixture, the common ion is Cl^-.The concentration of Cl^- ions increases and according to Le Chatelier's principle, the reaction that uses up some of the Cl^- ions will be favoured. In this reaction, the reverse reaction will be favoured and the reaction mixture turns blue.

2. Using Le Chatelier's principle to explain the effect of a change in temperature on equilibrium.



All reactions can be classified according to their energy changes as either **endothermic reactions** or exothermic reactions.

Endothermic reaction (Reaction that absorbs energy)	**Exothermic reaction (Reaction that releases energy)**
An endothermic reaction: • Absorbs more energy than it releases. • Therefore, the heat of the reaction (enthalpy change) is positive • ($\triangle H > 0$)	An exothermic reaction: • releases more energy than it absorbs • Therefore, the heat of the reaction (enthalpy change) is negative • ($\triangle H < 0$)
How to identify an endothermic reaction in real life? An endothermic reaction causes the reaction mixture to decrease in temperature i.e., reaction mixture feels cooler/cold. 	**How to identify a exothermic reaction in real life?** A exothermic reaction causes the reaction mixture to increase in temperature i.e., reaction mixture feels warmer/hot. 

Effect of a change in temperature on the equilibrium of the system:

According to Le Chatelier's principle, if the temperature of a reaction mixture is changed, the system will respond to **counteract/oppose the change**.

PRO-TIPS

Ways to increase the temperature of the reaction mixture: Heat the reaction mixture using a bunsen burner or a hot plate.

Increasing the temperature of the reaction mixture

- If the temperature of the reaction mixture is increased the system will respond to counteract the change by favouring the reaction that decreases the temperature of the reaction mixture.
- The **endothermic reaction** ($\triangle H > 0$) is the reaction that decreases the temperature of the reaction mixture and is therefore **favoured (i.e., takes place at a faster rate)**.

Decreasing the temperature of the reaction mixture

- If the temperature of the reaction mixture is decreased the system will respond to counteract the change by favouring the reaction that increases the temperature of the reaction mixture.
- The **exothermic reaction** (∆H < 0) is the reaction that increases the temperature of the reaction mixture and is therefore **favoured (i.e., takes place at a faster rate)**.

PRO-TIPS

Ways to decrease the temperature of the reaction mixture: Place the reaction mixture in a beaker/ bucket of ice water or in a fridge or freezer.

NOTE:

- If the forward reaction is endothermic (∆H > 0), then the reverse reaction is exothermic (∆H < 0) and vice versa.

Endothermic
⇌
Exothermic

OR

Exothermic
⇌
Endothermic

- Therefore, for changes in temperature it is important to determine which two reactions- forward or reverse- is exothermic and which reaction - forward or reverse- is endothermic.
- The endothermic reaction is often **more** affected by a change in temperature than the exothermic reaction.

Worked example

A + P

1. Nitrogen (IV) oxide gas is prepared by dropping concentrated nitric acid on a few pieces of copper in a flask. A stopper is then placed firmly on the flask to prevent the gas from escaping.The colour of nitrogen (IV) oxide gas (NO_2) is a reddish – brown in colour. The following reversible reaction is taking place:

$$\underset{\text{brown}}{2NO_2(g)} \rightleftharpoons \underset{\text{colourless}}{N_2O_4(g)}$$

EXPERIMENT 1

The flask containing $NO_2(g)$ is now placed in a beaker containing hot water.

Observation: The colour of the of the gas gets darker, i.e. we say that the brown colour intensifies.

1.1 Is the above reaction an example of an ENDOTHERMIC or EXOTHERMIC reaction? (2)

1.2 Explain, using Le Chatelier's Principle, the observation observed in EXPERIMENT 1. (4)

EXPERIMENT 2

The flask is placed into a beaker which is filled with ice water.

1.3 Write down an independent variable for EXPERIMENT 1 and EXPERIMENT 2. (1)

1.4 Write down a controlled variable for EXPERIMENT 1 and EXPERIMENT 2. (1)

1.5 What will be observed in EXPERIMENT 2? Explain the answer. (4)

1.1 **How to approach the question:**

Note the observation: The brown colour intensifies - what does this observation mean looking at the reaction?

There is higher concentration of NO_2 (g) due to more moles of NO_2(g) being produced per second. This indicates that the reverse reaction is being favoured.

What factor affecting the equilibrium of the system?

The flask containing NO_2(g) was placed in a beaker containing **hot water**.

Therefore, temperature of the reaction mixture was increased. According to Le Chatelier's principle, the system will respond to counteract the change by favouring the reaction that decreases the temperature of the reaction mixture i.e., **the endothermic reaction**.

Therefore, because it was concluded that the reverse reaction is being favoured, the reverse reaction is endothermic and the reaction above (i.e., the forward reaction) is therefore **exothermic.**

1.2

Remember: Tips for explaining answers using Le Chatelier's Principle:

- State the factor being changed (i.e., a change in concentration/temperature/pressure of a gaseous system)
- Use Le Chatelier's principle to determine how the system will respond to counteract the change.
- Determine reaction (forward or reverse) will favoured (i.e. take place at a faster rate)
- Draw a conclusion (based on the question asked).

PRO-TIPS

If the question specifies "for this reaction" it implies the **forward reaction.**
Only if it specifies the **reverse reaction** is information regarding the **reverse reaction** required.

- In this reaction, it was observed that the brown colour intensifies when the temperature of the reaction mixture is increased.
- According to Le Chatelier's principle, when the temperature of the reaction mixture is increased, the system will respond to counteract the change by favouring the reaction that decreases the temperature of the reaction mixture, i.e., the **endothermic reaction**.
- Due to the concentration of NO_2(g) increasing, the reverse reaction is being favoured and is therefore the endothermic reaction.

NOTE: The TYPE of reaction (endothermic reaction or exothermic reaction) must be stated.

1.3 The independent variable in an experiment is the variable that is being deliberately changed or manipulated.
In experiment 1, the reaction mixture was placed in a beaker containing hot water to increase its temperature.
In experiment 2, the reaction mixture was placed in a beaker filled with ice water.
Therefore, the variable being changed in this experiment is the **temperature.**
∴ Independent variable: Temperature

1.4 The controlled variable is the variable that is kept constant in an experiment.
This reaction is determining how a change in temperature affects the equilibrium of the system, therefore all the other factors that affect the equilibrium of the system must be kept constant, such as pressure (note that all reactants and products are gases), concentration of all gases.
∴ Controlled variable: Pressure/concentration (of all gases)

1.4 **How to approach the question:**

Determine what factor is affecting the equilibrium of the system?

The flask was placed in a beaker containing **ice water**.

Therefore, temperature of the reaction mixture was decreased. According to Le Chatelier's principle, the system will respond to counteract the change by favouring the reaction that increases the temperature of the reaction mixture i.e., **the exothermic reaction**.

It was concluded that the forward reaction is **exothermic,** therefore more N_2O_4 (g) will be produced each second and the reaction mixture will turn from brown to colourless.

NOTE: In your explanation, reference and use Le Chatelier's principle to determine how the system will respond to the equilibrium being disturbed.

The reaction mixture will turn from brown to colourless or the reaction mixture will turn colourless.

- In experiment 2, the temperature of the reaction mixture was decreased.
- According to Le Chatelier's principle, the reaction that will be favoured is the reaction that increases the temperature of the reaction mixture i.e., the exothermic reaction.
- In this reaction, the forward reaction is the exothermic reaction and will therefore be favoured.
- The concencentration of colourless N_2O_4(g) will increase, as more N_2O_4(g) is being produced per second. The reaction mixture will turn from brown to colourless.

2. Using Le Chatelier's principle to explain the effect of a change in pressure (of gases) on equilibrium.

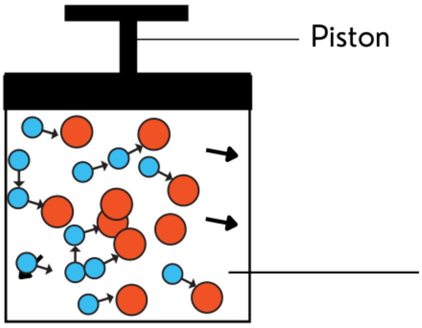
A change in pressure can only affect the equilibrium of a system if the following conditions are met simultaneously:

1. The system is a gaseous system, where at least one of the reactants or products is a gas.
2. The system must be able to respond to a change in pressure i.e. the total the number of moles of gas in the reactants and products **differ**.

NOTE: The **pressure of the gaseous system is changed**, by **changing the volume of the container, since pressure of a gas is inversely proportional to the volume**.

Figure 1 below represents a closed container/vessel filled with gas. A piston which can be moved up and down is used to change the volume of the container and hence the pressure in the closed container.

Figure 1

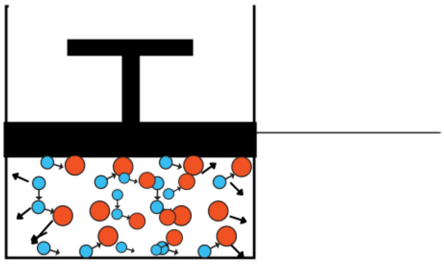


Remember: Gases take up the shape and the entire volume of the container

- In **figure 1** above, due to the **increased volume**, the gas particles are further apart and there are fewer collisions between the gas particles and the sides of the container.
- Therefore, there is a **lower pressure** in the closed container or vessel.

Figure 2 below represents a closed container/vessel filled with gas. The piston is being pushed down to decrease the volume of the container/vessel and hence the volume of gas. The pressure of the system is increased.

Figure 2



Piston pushed down to decrease the volume of the container and increase the pressure of the system

- In **figure 2** above, due to the **decreased volume**, the gas particles are forced closer together and there are more collisions between the gas particles and the sides of the container.
- Therefore, there is a **greater pressure** in the closed container or vessel.

Effect of a change in pressure of gases on the system

According to Le Chatelier's principle, if the pressure of a gaseous system is changed (by changing the volume of the container), the system will **respond to counteract/oppose the change**.

Decreasing the pressure of the gaseous system by increasing the volume of the container

Example:

Consider the following reaction at equilibrium. The gas is in a sealed container:

$$2NO_2\,(g) \rightleftharpoons N_2O_4\,(g)$$

From the balanced reaction determine the number of moles of gas in the reactants and products:

2 moles of gas ↓ Greater number of moles of gas in reactants

1 mole of gas ↓ Fewer moles of gas in products

PRO-TIPS

When determining the number of moles of gas in reactant and products, only work with the reactants and products that are **gases.** Solids, liquids and aqueous solutions can be ignored.

1. The volume of the container is increased. What effect will this have on the concentration of NO_2 and N_2O_4?

NOTE: By increasing the volume of the container, the pressure of the system decreases.

- According to Le Chatelier's principle, when the pressure of the system is decreased (by increasing the volume of the container), the reaction that will be favoured is the reaction that counteracts the change i.e., the reaction that increases the pressure of the system i.e., the reaction that produces a greater number of moles of gas.
- In this example, the reverse reaction will be favoured (as it produces a greater number of moles of gas).
- The concentration of $NO_2\,(g)$ increases and the concentration of $N_2O_4\,(g)$ decreases.

2. The volume of the container is decreased. What effect will this have on the concentration of NO_2 and N_2O_4 ?

NOTE: By decreasing the volume of the container, the pressure of the system increases.

- According to Le Chatelier's principle, when the pressure of the system is increased (by decreasing the volume of the container), the reaction that will be favoured is the reaction that counteracts the change i.e., the reaction that decreases the pressure of the system i.e., the reaction that produces fewer/ less of moles of gas.
- In this example, the forward reaction will be favoured (as it produces fewer/less moles of gas).
- The concentration of NO_2(g) decreases and the concentration of N_2O_4 (g) increases.

Worked example

C + A

Multiple choice question

1. The Haber Bosch process is represented below:

$$3H_2(g) + N_2(g) \rightleftharpoons 2NH_3(g)$$

The volume of the container is changed and the concentration of the N_2 (g) decreases. Which ONE of the following represents the change to the volume of the container and the number of moles of NH_3 (g) produced?

	Volume of the container	Number of moles of NH_3 produced
A	Decreases	Decreases
B	Decreases	Increases
C	Increases	Decreases
D	Increases	Increases

Answer: B

N_2 (g) is a reactant. Due to its concentration decreasing, this means that the forward reaction is being favoured as a result of a change to the volume of the container and pressure of the system. Analyse the number of moles of gas in reactants and products:

$$\underbrace{3H_2(g) + N_2(g)}_{\text{4 moles of gas}} \rightleftharpoons \underbrace{2NH_3(g)}_{\text{2 moles of gas}}$$

4 moles of gas ↓ Greater number of moles of gas in reactants

2 moles of gas ↓ Fewer moles of gas in products

Volume of the container

It was concluded that the forward reaction was favoured. The forward reaction produces fewer moles of gas, therefore decreasing the pressure of the system, this indicates that the pressure of the system was increased, by **decreasing the volume of the container.**

Number of moles of NH_3 produced

It was concluded that the forward reaction was favoured. Therefore more NH_3 is being produced per second, the number of moles (and concentration) of NH_3 increases.

NOTE the following example, where carbon reacts with oxygen gas to produce carbon dioxide gas

Example: $C\ (s) + O_2\ (g) \rightleftharpoons CO_2\ (g)$

$$C\ \cancel{(s)} + O_2\ (g) \rightleftharpoons CO_2\ (g)$$

1 mole of gas

Same number of moles of gas in reactants as products

1 mole of gas

Same number of moles of gas in products as reactants

PRO-TIPS

When determining the number of moles of gas in reactant and products, only work with the reactants and products that are **gases.** Solids, liquids and aqueous solutions can be ignored.

- If there is the same number of moles of gas on both sides of the equilibrium reaction increasing or decreasing the pressure has **no effect on the equilibrium of the system,** since the system cannot produce more or less moles of gas to increase or decrease the pressure of the system.
- If the pressure is increased the concentration of the reactants and products will increase equally. The rate of both reactions will increase equally.
- If the pressure is decreased, the concentration of the reactants and products will decrease equally. The rate of both reactions will decrease equally.

Factors that DO NOT affect the equilibrium of the system

While a change in temperature, pressure of gases and the concentration of gases and aqueous solutions does affect the equilibrium of a system because it changes the concentration of the reactants and products, the following factors **do not** affect the equilibrium of the system:

- **Adding or removing a pure solid reactant or product (at equilibrium).** The concentration of a pure solid does not change, therefore it does not change the concentration of other reactants and products at equilibrium.
- **Adding or removing of a pure liquid reactant or product (at equilibrium).** The concentration of a pure liquid does not change, therefore it does not change the concentration of other reactants and products at equilibrium.
- **Adding a catalyst**

Why does adding a catalyst after equilibrium is reached not affect the equilibrium of a system?

- If a catalyst is added to a reaction at equilibrium, both the forward and reverse reaction rates will increase **equally**.
- If both reaction rates increase **equally** then the concentrations of all gaseous and aqueous solution reactants and products will **remain constant.**
- Therefore, the addition of a catalyst does not affect (or change) the equilibrium of a system.

Effect of adding a catalyst before equilibrium is reached

- Both the forward and the reverse reaction will proceed at a faster rate with the addition of a catalyst.
- Equilibrium will be reached sooner and the concentration of the reactants and products at equilibrium are the same as when a catalyst was not added to the reaction.

Worked example

1. Consider the following reaction which is called the Contact process used to produce SO_3 which is used in the production of H_2SO_4 (sulphuric acid). The reaction is at equilibrium.

$$2SO_2\,(g) + O_2\,(g) \rightleftharpoons 2SO_3\,(g) \quad \Delta H = -198\ kJ$$

1.1 Is the forward reaction an ENDOTHERMIC or EXOTHERMIC reaction? Explain the answer. (2)

1.2 Write down THREE ways that the yield of SO_3 can be increased? (3)

1.3 A catalyst, vanadium pentoxide, is added after the reaction reached equilibrium. How will this affect the concentration of SO_3(g)? Write down INCREASES, DECREASES or REMAINS THE SAME. Explain the answer. (3)

1.1

Tips for identifying if a reaction is endothermic or exothermic:

Exothermic reaction	**Endothermic reaction**
The enthalpy change is given: $\Delta H < 0$ **OR** $\Delta H = -x$ kJ	**The enthalpy change is given**: $\Delta H > 0$ **OR** $\Delta H = +x$ kJ
The energy is a **product,** as more energy is released than absorbed.	The energy is a **reactant,** as more energy is absorbed than released.

Exothermic. The enthalpy change (or heat of the reaction) is negative **OR** $\Delta H < 0$ **OR** more energy is released than absorbed.

1.2 To increase the yield of SO_3(g), which is a product in the reaction, the forward reaction must be favoured (i.e., take place at a faster rate). There are many ways to increase the rate of the forward reaction by changing the reaction conditions to change the equilibrium of the system:

1) Change in temperature: the forward reaction is an exothermic reaction, therefore according to Le Chatelier's principle, to favour the exothermic reaction, the **temperature of the reaction mixture must be decreased.**
(However, note that this also decreases the rate of the reaction!)

2) Change in pressure of system

$$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$$

3 moles of gas — Greater number of moles of gas in reactants

2 moles of gas — Fewer moles of gas in products

To favour the forward reaction, which produces fewer moles of gas, according to Le Chatelier's principle, **the pressure of the system must be increased (by decreasing the volume of the container).**

3) Change in concentration

To favour the forward reaction, according to Le Chatelier's principle, $SO_3(g)$ must be removed from the system, to ensure that the forward reaction is favoured to produce more SO_3 (g).

OR

the concentration of the reactants SO_2(g) **or/and** O_2(g) must be increased. This will favour the forward reaction to use up the reactant/s.

1.3

Remember: The addition of a catalyst **AFTER** equilibrium is reached, does not change the equilibrium of the system as the rate of both the forward and reverse reaction increases **EQUALLY**. The concentrations of all reactants and products remain constant.

∴ REMAINS THE SAME. Adding a catalyst after equilibrium is reached **increases the rate of both the forward and reverse reaction equally**, therefore it **does not change the equilibrium of the system**. The concentration of SO_3(g) therefore remains constant.

THE EQUILIBRIUM CONSTANT (K_c)

Scientists deduced that there is a mathematical relationship between the concentrations of reactants and the products at equilibrium. This is the equilibrium constant, K_c . The 'c' indicates concentration.

The equilibrium constant (K_c) is a **ratio of the concentration of the products to the concentration of reactants** for a reaction at equilibrium.

The K_c value for a reaction at equilibrium can be expressed using this **general equation:**

$$\boxed{K_c = \frac{\text{concentration of the products}}{\text{concentration of the reactants}}}$$

OR

$$\boxed{K_c = \frac{[products]}{[reactants]}}$$

PRO-TIPS

This general Kc expression will not be accepted in a test or exam, a specific Kc expression must be written for the chemical reaction, which will be discussed later.

What do these variables mean and what are the SI units?

[ ] = concentration in $mol.dm^{-3}$

[products] = concentration of products in $mol.dm^{-3}$

[reactants] = concentration of reactants in $mol.dm^{-3}$

K_c = equilibrium constant (no units, as it is a ratio)

Which concentrations can be substituted into the K_c expression?

Only the concentrations **at equilibrium** of the following states of matter:

- ✓ Gases (g)
- ✓ Aqueous solutions (aq)

… because the concentration of a gas and an aqueous solution can change and therefore it determines the K_c value for a reaction at a specific temperature.

Which concentrations cannot be substituted into the K_c expression?

- ✗ Pure solids (s)
- ✗ Pure liquids (ℓ)

- The concentration of a pure solid (s) and a pure liquid (l) remains constant during the reaction (i.e. the concentration of a solid and a pure liquid does not change).
- The concentration of a pure solid and a pure liquid is therefore taken as 1 and can be **omitted from the K_c expression.**

Writing a K_c expression

Consider the hypothetical reaction shown below (assume the states of matter of all substances to be gases):

$$aA + bB \rightleftharpoons cC + dD$$

The equilibrium expression for this hypothetical reaction can be written as:

$$K_c = \frac{[C]^c[D]^d}{[A]^a[B]^b}$$

Where [ ] = concentration

NOTE: the concentrations of the reactants and products are raised to the coefficients from the balanced chemical equation.

What does the K_c value represent?

In the K_c expression, the concentrations of the products appear in the numerator and the concentrations of the reactants appear in the denominator.
Therefore, the K_c value gives an indication of the yield of the reaction (the amount of product produced in the reaction).

- A high K_c value is a K_c value greater than 1 ($K_c > 1$) → **numerator bigger than denominator**
  indicates that the reaction produces a **high yield**, i.e. there is a higher concentration of products than reactants. For industrial processes, a high yield is important.

- A low K_c value is a K_c value smaller than 1 ($K_c < 1$) → **denominator bigger than denominator**
  indicates that the reaction produces a **low yield**, i.e. there is a higher concentration of reactants than products.

- $K_c = 1$ indicates that [products] = [reactants] → **numerator equals denominator**

Worked example

1. Write down a K_c expression for the following reactions:

1.1 $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$

In this reaction, all the reactants and products are gases, and therefore their concentrations are included in the K_c expression.

Remember: the concentrations of the substances are raised to the power of the coefficient from the balanced equation.

$$K_c = \frac{[NH_3]^2}{[N_2][H_2]^3}$$

1.2 $CaO(s) + CO_2(g) \rightleftharpoons CaCO_3(s)$

In this reaction, only CO_2 is a gas (the other reactants and products are solids), and therefore only the concentration of CO_2 will be included in the K_c expression.

$$K_c = \frac{1}{[CO_2].1}$$

$$\therefore K_c = \frac{1}{[CO_2]}$$

PRO-TIPS

The Kc value is calculated from a balanced chemical equation. Note the following:

- The reaction must be balanced.
- Pure solids (s) and pure Liquids (l) are not included in Kc expressions as their concentrations never change.

Factor that affects the K_c value

- The only factor that affects the K_c value of a reaction is a **change in temperature**.
- Only a change in temperature can result in the ratio of the concentration of products and the concentration of reactants changing.

NOTE: A change in the following factors will **NOT** affect the K_c value:

- A change in the concentration of a gaseous or aqueous solution reactant or product.
- A change in pressure (of a gaseous system).
- The addition of a catalyst.
- A change in the mass of a pure solid or the volume of a pure liquid.

While changing these two factors changes the equilibrium of the system, **it does not change the ratio of the concentration of the products to reactants, therefore it does not change the K_c value.**

Effect of a change in temperature on K_c value

GENERAL CONCLUSIONS:

- If the K_c value increases due to a change in temperature, the forward reaction was favoured.
- If the K_c value decreases due to a change in temperature, the reverse reaction was favoured.
- If the forward reaction is exothermic, increasing the temperature favours the reverse, endothermic reaction according to Le Chatelier's principle and therefore decreases the value of the equilibrium constant.
- If the forward reaction is endothermic, increasing the temperature favours the forward, endothermic reaction according to Le Chatelier's principle and therefore increases the value of the equilibrium constant.

CALCULATING THE EQUILIBRIUM CONSTANT (K_c)

To calculate the concentrations of the reactants and products at equilibrium, the initial amounts of the reactants and products and the amounts used up and produced during the reaction need to be kept track of to determine the concentrations at equilibrium.

A method commonly called the '**RICE C table**' or '**RICE table**' is used to determine the concentrations at equilibrium.

OPTION 1: Working with the number of moles to determine the equilibrium concentration

Ratio	**Mole ratio** of reactants and products from the **balanced reaction**
Initial mol	**Initial number of moles** of the reactants or products at the start of the reaction.
Change in mol	**Number of moles used up (reactants) or produced (products) during the reaction.** **Remember:** the substances are used up and produced in the correct mole ratios according to the balanced reaction.
Equilibrium mol	**Number of moles** of reactants and products **at equilibrium.**
Concentration at equilibrium $c = \frac{n}{V}$	**Concentration** of reactants and products **at equilibrium.** Formula to convert the number of moles (of reactants and products) at equilibrium to the **equilibrium concentrations** (used to calculate the K_c value): $c = \frac{n}{V}$

PRO-TIPS

SI units for volume: dm^3
NOTE: $1\ell = 1\ dm^3$
Conversion chart:
$cm^3 \rightarrow dm^3 \div 1000$
$ml \rightarrow dm^3 \div 1000$

Remember: Only the concentrations of gases (g) and aqueous solutions (aq) at equilibrium are used to determine the K_c value.
However, sometimes the initial moles of a pure solid is needed to determine these concentrations of gases and aqueous solutions at equilibrium.

OR

PRO-TIPS

This method is useful if the concentrations are given.

OPTION 2: Working with the concentrations → $c = \frac{n}{V}$

Ratio	**Mole ratio** of reactants and products from the **balanced reaction**.
Initial concentration	**Initial concentration** of the reactants or products at the start of the reaction. $c = \frac{n}{V}$
Change in concentration	**Change in concentration of reactants and products during the reaction.** **Remember:** the substances are used up and produced in the correct mole ratios according to the balanced reaction.
Equilibrium concentration	**Concentration of reactants and products at equilibrium.**

Worked example

1. A mixture of H_2 and I_2 reacts at 400°C in a 2 dm^3 container, according to the following equation:

$$H_2 (g) + I_2 (g) \rightleftharpoons 2HI (g) \quad \Delta H < 0$$

At equilibrium, the container holds 1,4 moles of H_2, 1,6 moles of I_2 and 4 moles of HI.

1.1 Calculate the value of the equilibrium constant for this reaction at 400°C. (4)

1.2 Explain what the K_c value calculated in QUESTION 1.1 means. (2)

1.3 The temperature of the reaction mixture is INCREASED. How will this affect the K_c value? Write down only INCREASES, DECREASES or REMAINS THE SAME. Explain the answer. (4)

1.4 0,5 moles of H_2 is added to the equilibrium mixture, how will this affect the K_c value?
Write down only INCREASES, DECREASES or REMAINS THE SAME. (2)

1.1 This is a basic, introductory question where the number of moles at equilibrium is already known. The '**RICE C**' method does not have to be used in this question. The equilibrium moles can be used to determine the equilibrium concentrations using the formula: $c = \frac{n}{V}$
The volume of the container (2 dm^3) is known. All the reactants and products are gases, therefore their concentrations will be used to determine the K_c value.

Equilibrium concentrations

c (H_2 at equilibrium) = $\frac{n}{V}$
c (H_2 at equilibrium) = $\frac{(1{,}4)}{(2)}$
c (H_2 at equilibrium) = 0,7 mol

c (I_2 at equilibrium) = $\frac{n}{V}$
c (I_2 at equilibrium) = $\frac{(1{,}6)}{(2)}$
c (I_2 at equilibrium) = 0,8 mol

c (HI at equilibrium) = $\frac{n}{V}$
c (HI at equilibrium) = $\frac{(4)}{(2)}$
c (HI at equilibrium) = 2 mol

PRO-TIPS

Gases take up the entire volume of the container.

Write a K_c expression and substitute the equilibrium concentrations into the K_c expression:

$K_c = \frac{[HI]^2}{[H_2][I_2]}$ → **K_c expression for this reaction**
$K_c = \frac{(2)^2}{(0{,}7)(0{,}8)}$
$K_c = 7{,}14$

PRO-TIPS

A specific K_c expression for the reaction must be written.

$K_c = \frac{[products]}{[reactants]}$ ✗

will **not earn a mark.**

1.2 If $K_c > 1$ ∴ high yield; [products] > [reactants]
If $K_c < 1$ ∴ low yield; [products] < [reactants]
If $K_c = 1$ ∴ [products] = [reactants]

The K_c value is greater than 1 ($K_c > 1$).
This indicates that the reaction has a high yield **OR**
This indicates that the concentration of the products is greater than the concentration of the reactants.

1.3 Determine which reaction (forward and reverse) is the endothermic and exothermic reaction:In this reaction, the forward reaction is **exothermic** ($\Delta H < 0$ given), therefore the reverse reaction is **endothermic** ($\Delta H > 0$).

Remember: Temperature is the only factor that can affect the K_c value.

Decreases

- According to Le Chatelier's principle, when the temperature of the reaction mixture is increased, the system responds to counteract that change by favouring the reaction that decreases the temperature of the reaction mixture, i.e., the endothermic reaction.
- In this reaction, the reverse endothermic reaction will be favoured.
- Therefore, the concentration of the products decreases, and the concentration of the reactants increases
- The K_c value decreases.

1.4 Adding more moles of $H_2(g)$ increases the concentration of $H_2(g)$. This will affect the equilibrium of the system and the system will respond by favouring the forward reaction, however, the ratio of the concentration of products to the concentration of reactants remains constant, therefore the K_c value remains constant.

Remember: The only factor that can change the K_c value is a change in temperature.

∴Remains the same

Worked example

2. 10 moles of CO (g) and 10 moles of $O_2(g)$ are placed in a sealed container of volume 2 dm^3 at 700 K, and the following equilibrium is set up:

$$2CO\ (g) + O_2\ (g) \rightleftharpoons 2CO_2(g)$$

At equilibrium there are 7 moles of CO_2 present in the container.

Calculate the value of the equilibrium constant for this reaction at 700 K. (6)

How to approach this question:

- The initial moles of CO (g) and $O_2(g)$ is known. The **RICE C** method will be useful in this question.
- The number of moles of $CO_2(g)$ at equilibrium is known, working backwards with this can be used to determine the number of moles of the other gaseous reactants and products at equilibrium and therefore the concentration of the gaseous reactants and products at equilibrium. The volume of the container is known.

$$2CO\ (g) \quad + \quad O_2(g) \quad \rightleftharpoons \quad 2CO_2(g)$$ ✓

Check that the reaction is balanced

	$2CO\ (g)$	$O_2(g)$	$2CO_2(g)$
Ratio	2	1	2
Initial mol	10 mol	10 mol	0 mol
Change in mol	7 mol $n(CO) = n(CO_2)$	3,5 mol $n(O_2) = \frac{1}{2}n(CO_2)$	7 mol
Equilibrium mol	10 - 7 = 3 mol	10 - 3,5 = 6,5 mol	7 mol
Concentration at equilibrium ($mol.dm^{-3}$)	1,5 $mol.dm^{-3}$	3,25 $mol.dm^{-3}$	3,5 $mol.dm^{-3}$

At the start of the reaction, there is no product produced.

(start with 0 mol and 7 mol at equilibrium, therefore 7 mol produced during the reaction).

Remember the reactants and products must react and produce in the correct mole ratios.

c (CO at equilibrium) = $\frac{n}{V}$
c (CO at equilibrium) = $\frac{(3)}{(2)}$
c (CO at equilibrium) = 1,5 $mol.dm^{-3}$

c (O_2 at equilibrium) = $\frac{n}{V}$
c (O_2 at equilibrium) = $\frac{(6,5)}{(2)}$
c (O_2 at equilibrium) = 3,25 $mol.dm^{-3}$

c (CO_2 at equilibrium) = $\frac{n}{V}$
c (CO_2 at equilibrium) = $\frac{(7)}{(2)}$
c (CO_2 at equilibrium) = 3,5 $mol.dm^{-3}$

$$K_c = \frac{[CO_2]^2}{[CO]^2[O_2]}$$

Specific K_c expression for this reaction. Note the exponents.

$$K_c = \frac{(3,5)^2}{(1,5)^2(3,25)}$$

$$K_c = 1,68$$

Worked example

3. 36 g of water vapour is placed in a closed container of volume 1 dm^3 and heated to 600°C . The following equilibrium is established:

$$C\,(s) + H_2O\,(g) \rightleftharpoons CO(g) + H_2\,(g)$$

The value of Kc for this reaction at 600°C is 1.
Calculate the mass of CO present in the container at equilibrium. (8)

How to approach this question:

- The initial mass of H_2O (g) is known. This can be used to calculate the initial moles.
- The **RICE C** method will be useful in this question as only the initial mass of H_2O is known.
- No information regarding the number of moles at equilibrium nor concentrations at equilibrium is known, however, the K_c value is known - working backwards with this can be used to determine the concentration of CO at equilibrium and thereafter the mass of CO_2 at equilibrium.

$$\mathbf{C\,(s) + H_2O\,(g) \rightleftharpoons CO(g) + H_2\,(g)}$$ ✓

Check that the reaction is balanced

n(H_2O initial) = $\frac{m}{M}$
n(H_2O initial) = $\frac{(36)}{(18)}$
n(H_2O initial) = 2 mol

M(H_2O) = 2(1) + 16
M(H_2O) = 18 $g.mol^{-1}$

Ratio	1	1	1	1
Initial mol	-	2 mol	0 mol	0 mol
Change in mol	-	**x** mol	**x** mol	**x** mol
Equilibrium mol	-	(2 - **x**) mol	**x** mol	**x** mol
Concentration at equilibrium ($mol.dm^{-3}$)	-	(2 - **x**) $mol.dm^{-3}$	**x** $mol.dm^{-3}$	**x** $mol.dm^{-3}$

Substances react in the same mole ratio (1: 1: 1: 1)

- The number of moles of all the substances at **equilibrium is unknown,** therefore it's not possible to work backwards.
- The number of moles of reactants and products used up and produced is unknown. The unknown is usually called **x**.
- All the substances react and produce in a mole ratio 1 : 1 (same ratio), therefore the number of moles of CO and H_2 produced is also x.

C(s) is a pure solid, therefore its concentration is taken as 1, and can therefore be omitted from the Kc expression.

c (H_2O at equilibrium) = $\frac{n}{V}$
c (H_2O at equilibrium) = $\frac{(2-x)}{(1)}$
c (H_2O at equilibrium) = (2 – x) $mol.dm^{-3}$

c (CO at equilibrium) = $\frac{n}{V}$
c (CO at equilibrium) = $\frac{(x)}{(1)}$
c (CO at equilibrium) = x $mol.dm^{-3}$

c (H_2 at equilibrium) = $\frac{n}{V}$
c (H_2 at equilibrium) = $\frac{(x)}{(1)}$
c (H_2 at equilibrium) = x $mol.dm^{-3}$

$K_c = \frac{[CO][H_2]}{[H_2O]}$

$(1) = \frac{(x)(x)}{(2-x)}$

$(1)(2-x) = x^2$

$2 - x = x^2$

$x^2 + x - 2 = 0$

$(x + 2)(x - 1) = 0$

~~$x = -2$~~ or $x = 1$

N/A

The concentration at equilibrium cannot be negative, this answer is not applicable to this question.

Remember: Quadratic formula:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Solving a quadratic equation:

- Get all the terms on one side, and equal to zero on the other side
- Factorise

Refer back to the RICE C table:

x = concentration of CO (g) at equilibrium = 1 mol.dm^{-3}

Do not lose track of what the question is asking: The mass of CO(g) at equilibrium.

c (CO at equilibrium) = $\frac{n}{V}$

$(1) = \frac{n}{(1)}$

n (CO at equilibrium) = 1 mol

Formula to convert moles to mass.

n(CO at equilibrium) = $\frac{m}{M}$

$(1) = \frac{m}{(28)}$

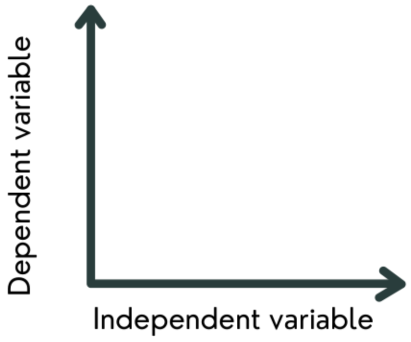
m(CO at equilibrium) = 28 g

M(CO) = 12 + 16

M(CO) = 28 g.mol^{-1}

CHEMICAL EQUILIBRIUM AND GRAPHS

- When a chemical reaction reaches equilibrium, the rate of the forward and reverse reaction is equal.
- The concentrations of all reactants and products remain constant at equilibrium. The temperature and pressure (of a gaseous system) also remains constant.
- When the equilibrium of a system is disturbed, the rate of the forward and reverse reaction is no longer equal and the concentrations of the reactants and products are no longer constant. This can be represented in a graph.
- The following graphs are common in this section:
  ✓ Reaction rate - time graph
  ✓ Concentration - time graph (or number of moles - time graph)



Example Consider the following reversible reaction in a closed system

$$A (g) + B (g) \rightleftharpoons C (g) + D (g)$$

This chemical reaction can reach equilibrium

Reaction - rate time graph

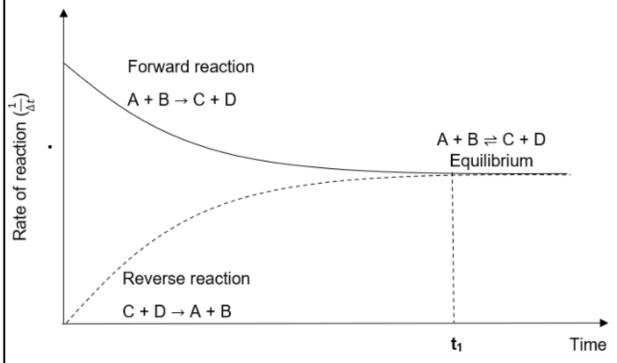


Figure 3

- Initially the concentration of the reactants A and B is high, and the rate of the forward reaction is high.
- As the reaction proceeds, the concentration of A and B decreases and results in the rate of the forward reaction decreasing. (indicated by the solid line in **figure 3** above)
- Initially there are no products C and D (reaction rate of reverse reaction initially 0).
- As reactant A and B get used up, products C and D are formed. As more products are produced per second, the rate of the reverse reaction increases. (Indicted by the dotted line in **figure 3** above).
- At time t_1 , both the forward and reverse reactions proceed at the same rate. The system has reached equilibrium: the rate of the forward and the reverse reaction are equal.

Concentration - time graph

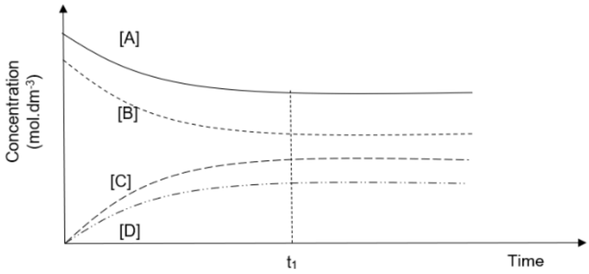


Figure 4

- Initially the concentration of the reactants A and B is high. As the reaction proceeds the concentration of the reactants decreases.
- Initially the concentration of products C and D is zero. As the reaction proceeds the concentration of the products increases.

When a chemical reaction reaches equilibrium:

- **AT A MACROSCOPIC LEVEL:** it appears as though nothing is happening and although it is not always possible to observe any macroscopic changes, this does not mean that the reaction has stopped. The forward and reverse reactions continue to take place and so microscopic changes still occur in the system. The system is in dynamic equilibrium.

- **AT A MICROSCOPIC LEVEL:** The concentrations of all the substances in the reaction mixture ([A], [B], [C], [D]), remain constant (but not necessarily equal) when the reaction reaches equilibrium (see **figure 4** above at time t_1)

Remember: Temperature and pressure (in the case of a gaseous system), remains constant when dynamic chemical equilibrium is reached.

Effect of a change in concentration on equilibrium - Graph explanations

Reactants

- Increasing the concentration of a reactant, increases the rate of the forward reaction (**sharp** increase).
- As more product is being produced per second, the rate of the reverse reaction **gradually** increases.
- The rate of forward reaction gradually decreases.
- After a certain time, the equilibrium of the system is re - established, but with new concentrations of the reactants and products. However, the K_c value remains unchanged.

OR

- Decreasing the concentration of a reactant, decreases the rate of the forward reaction (**sharp** decrease).
- As less product is being produced per second, the rate of the reverse reaction **gradually decreases** (but is still favoured as it is faster than the rate of the forward reaction)**.**
- The rate of forward reaction gradually increases.
- After a certain time, the equilibrium of the system is re - established, but with new concentrations of the reactants and products. However, the K_c value remains unchanged.

Products

- Increasing the concentration of a product, increases the rate of the reverse reaction (**sharp** increase).
- As more reactant is being produced per second, the rate of the forward reaction **gradually** increases.
- The rate of the reverse reaction gradually decreases.
- After a certain time, the equilibrium of the system is re - established, but with new concentrations of the reactants and products. However, the K_c value remains unchanged.

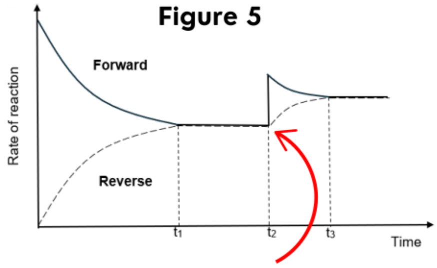
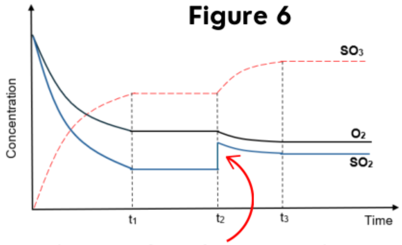
OR

- Decreasing the concentration of a product, decreases the rate of the reverse reaction (sharp decrease).
- As less reactant is being produced per second, the rate of the forward reaction **gradually decreases** (but is still favoured as is faster than the rate of the reverse reaction)**.**
- The rate of the reverse reaction gradually increases.
- After a certain time, the equilibrium of the system is re - established, but with new concentrations of the reactants and products. However, the K_c value remains unchanged.

Example: $2SO_2\ (g) + O_2\ (g) \rightleftharpoons 2SO_3\ (g)$

- At time t_1, the system reaches equilibrium.
- At time t_2, the concentration of SO_2 (g) is **increased.**
- At time t_3, the equilibrium of the system is re- established.

This is graphically represented in **figure 5** and **figure 6** below:

Reaction - rate time graph	**Concentration - time graph**
Figure 5  At time t_2 there is a **sharp increase** in the rate of the forward reaction **only** when SO_2 (g) reactant is added to the system. The reverse reaction gradually increases. A new equilibrium is established.	**Figure 6**  At time t_2 there is a **sharp increase** in the concentration of SO_2 (g) reactant only. The forward reaction is favoured to use up the SO_2 (g), therefore the concentration of O_2 (g) (reactant) gradually decreases and the concentration of SO_3 (product) gradually increases

NOTE: General conclusions regarding a change in concentration of a reactant or product:

Reaction- rate - time graph

- **Reactant or product added:** Sharp increase in ONE of the reaction rates only. Gradual increase in rate of the other reaction.
- **Reactant or product removed:** Sharp decrease in ONE of the reaction rates only. Gradual decrease in rate of the other reaction.

Concentration- time graph

- **Reactant or product added:** Sharp increase in the concentration of the reactant or product added only.
- **Reactant or product removed:** Sharp decrease in the concentration of the reactant or product removed only.

Effect of a change in temperature on equilibrium - Graph explanations

Increase in temperature

Reaction - rate time graph

- An increase in temperature results in an increase in the average kinetic energy of the particles of **all** the reactants and products.
- The rate of **both** the forward and the reverse reaction will **sharply increase,** however, the rate of the endothermic reaction increases **more** than the rate of the exothermic reaction (i.e., there is an even sharper increase in the rate of the endothermic reaction than the exothermic reaction).

Concentration - time graph

- No sharp increase or decrease in the concentration of any gaseous or aqueous solution reactants or products (only gradual changes), due to the rate of both the forward and reverse reaction sharply increasing.

Decrease in temperature

Reaction - rate time graph

- A decrease in temperature results in a decrease in the average kinetic energy of the particles of **all** the reactants and products.
- The rate of **both** the forward and the reverse reaction will **sharply decrease,** however, the rate of the exothermic reaction decreases **less sharply** than the rate of the endothermic reaction.

Concentration - time graph

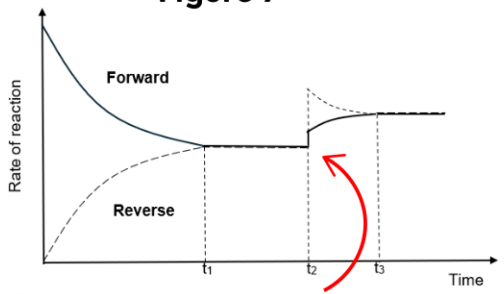
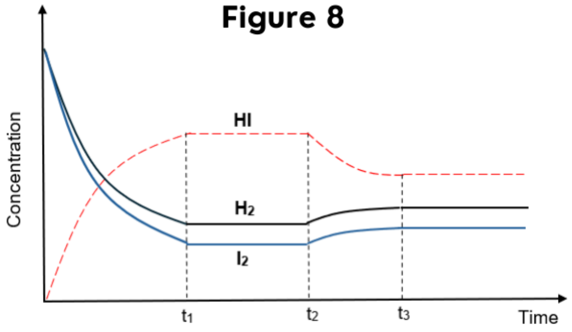
- No sharp increase or decrease in the concentration of any gaseous or aqueous solution reactants or products (only gradual changes), due to the rate of both the forward and reverse reaction sharply decreasing.

Example: $H_2(g) + I_2(g) \rightleftharpoons 2HI(g) \quad \Delta H < 0$ →

NOTE: the forward reaction is exothermic, therefore the reverse reaction is endothermic

- At time t_1 , the system reaches equilibrium.
- At time t_2 , the temperature is **increased.**
- At time t_3, the equilibrium of the system is re - established.

This is graphically represented in **figure 7** and **figure 8** below:

Reaction - rate time graph	Concentration - time graph
Figure 7  • Temperature was increased at t_2, therefore, sharp (dramatic) increase in the rate of both the forward and reverse reaction. • However, there is a sharper increase in the rate of the reverse, endothermic reaction, as this is the reaction being favoured to decrease the temperature of the reaction mixture. • Thereafter, the concentration of reactants $H_2$and I_2 increases, increasing the rate of the forward reaction **gradually.** • The concentration of product HI decreases, decreasing the rate of the reverse reaction **gradually.** • **A new equilibrium is established.**	**Figure 8**  • Gradual change in the concentration of all gaseous reactants and products. • concentration of products (HI) decreases **gradually.** • concentration of reactants (H_2 and I_2) increases **gradually.** • K_c value changes as the ratio of concentration of products and reactants changes. (in this example the K_c value will decrease)

Effect of a change in pressure of gaseous system on equilibrium - Graph explanations

- Changing the volume of the container changes the pressure of the system, which changes the concentration of all gaseous reactants and products.

Increase in pressure

Reaction - rate time graph

- **Increasing** the **pressure** of the system by **decreasing** the **volume** of the container will sharply increase the rate of both the **forward** and **reverse reaction**, because the concentration of all gaseous reactants and products will sharply increase.
- **However**, the reaction that produces **fewer moles** of gas (to decrease the pressure of the system) will increase **more** than the reaction that produces more moles of gas.

Concentration - time graph

- **Increasing** the **pressure** of the system by **decreasing** the **volume** of the container will initially **sharply increase** the concentration of all gaseous reactants and products.
- **Thereafter**, a gradual change to the concentrations of all reactants and products is observed.

Decrease in pressure

Reaction - rate time graph

- **Decreasing** the **pressure** of the system by **increasing** the **volume** of the container will sharply decrease the rate of both the **forward** and **reverse** reaction, because the concentration of all gaseous reactants and products will sharply decrease.
- **However**, the reaction that produces a **greater** number of **moles** of gas (to increase the pressure of the system) will decrease **less sharply** than the reaction that produces less moles of gas.

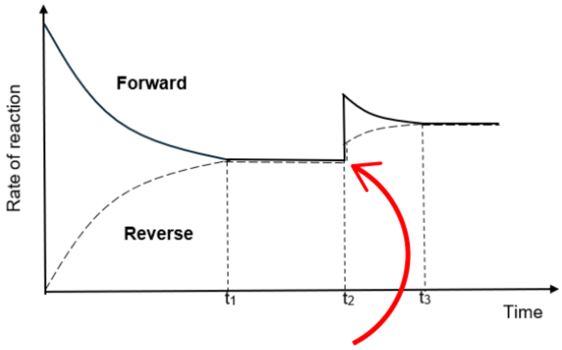
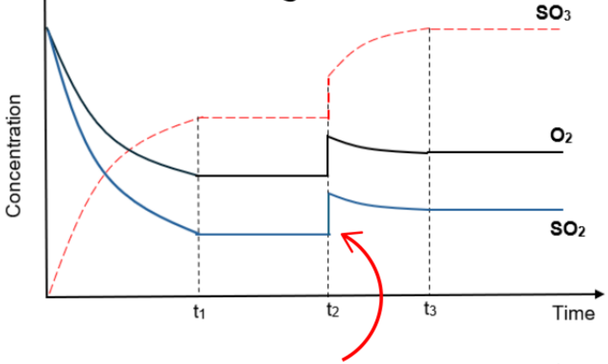
Concentration - time graph

- **Decreasing** the **pressure** of the system by **increasing** the **volume** of the container will initially sharply decrease the concentration of all gaseous reactants and products.
- **Thereafter**, a gradual change to the concentrations of all reactants and products is observed.

Example: $2SO_2\ (g) + O_2(g) \rightleftharpoons 2SO_3\ (g)$

- At time t_1, the system reaches equilibrium.
- At time t_2, the pressure of the system is **increased.**
- At time t_3, the equilibrium of the system is re - established.

This is graphically represented in **figure 9** and **figure 10** below:

Reaction - rate time graph	**Concentration - time graph**
Figure 9  • Pressure of the system was increased at time t_2. Therefore, the concentration of all gaseous reactants and products sharply increases and the rate of **both** the forward and reverse reaction **sharply increases**. • However, the forward reaction produces fewer moles of gas (2 moles of gas) compared to the reverse reaction that produces 3 moles of gas. • The forward reaction is favoured, and there is a sharper increase in the rate of the forward reaction than the reverse reaction. • Thereafter, the concentration of SO_2 (g) and O_2 (g) decreases, decreasing the rate of the forward reaction gradually. • The concentration of SO_2 (g) increases, increasing the rate of the reverse reaction gradually. • A new equilibrium is established.	**Figure 10**  • Initial sharp increase in the concentration of all gaseous reactants and products. • However, the forward reaction was favoured, therefore, the concentration of the reactants O_2 (g) and SO_2(g) gradually decreases and the concentration of product SO_2 (g) gradually increases.

Effect of a catalyst on equilibrium - Graph explanations

A catalyst is a substance that increases the rate of a chemical reaction without itself undergoing a permanent change. Many industrial processes use catalysts to increase the rate of production.

To determine how a catalyst affects the equilibrium of a system, you need to consider WHEN the catalyst was added:

- The catalyst added at the start of the reaction, before equilibrium is reached.
- The catalyst is added after equilibrium is reached.

The catalyst is present before equilibrium is reached (I.e., at the start of the reaction).

- Both the forward and the reverse reaction will proceed at a faster rate with the addition of a catalyst.
- Equilibrium will be reached sooner, and the concentration of the reactants and products at equilibrium are the same as when a catalyst was not added to the reaction.

Figure 11 below: Reaction - rate time graph representing a chemical reaction with a catalyst and without a catalyst.

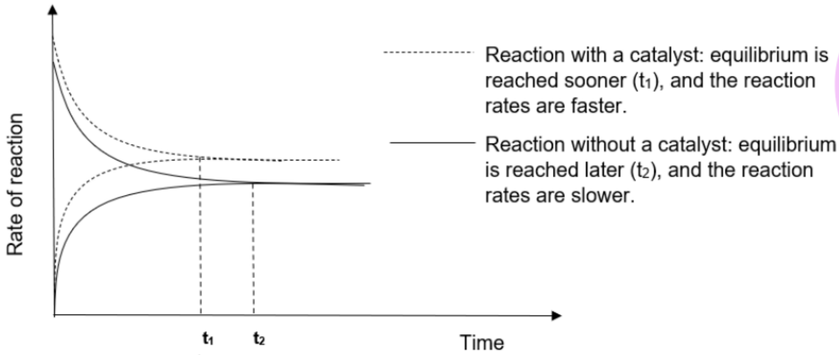


Figure 11

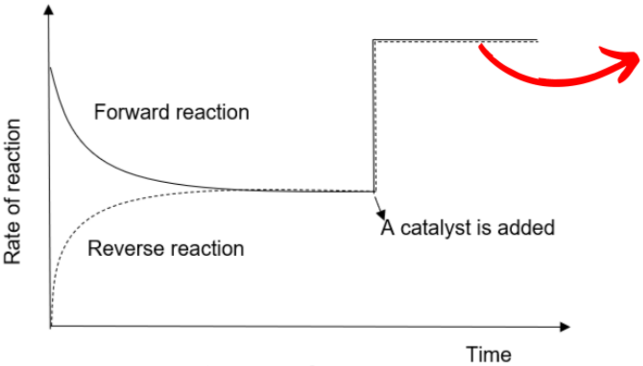
PRO-TIPS

A catalyst **increases** the rate of chemical reaction by **lowering** the **activation** energy and providing an alternative pathway for the reaction to take place. A catalyst **does not change** the average **kinetic** energy of the particles.

The catalyst is added after equilibrium has been reached

- If the catalyst is added after equilibrium has been reached, the reaction rate of both the forward and the reverse reactions increase **equally.**
- If both rates increase equally, **the concentrations of all reactants and products will remain constant and do not change** – the substances are just being used up and produced at a faster rate due to the addition of a catalyst. The equilibrium of the system is not disturbed.

Figure 12 below: Reaction - rate time graph representing a chemical reaction with a catalyst added **after** equilibrium is reached.



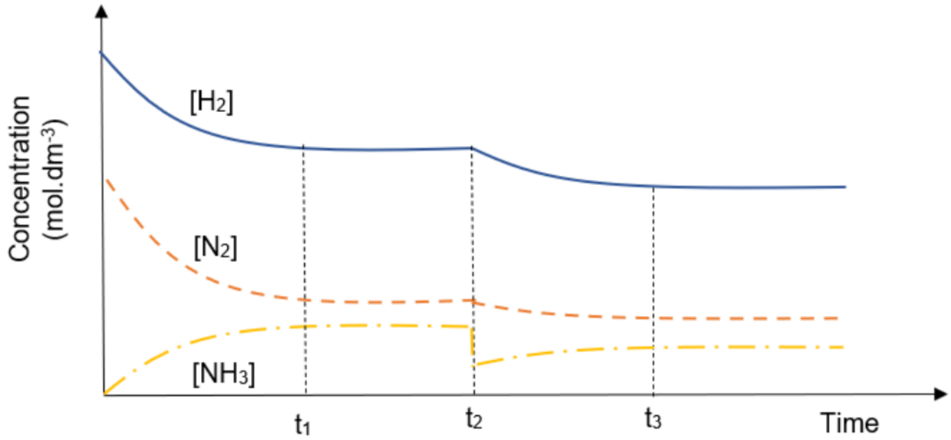
NOTE: When a catalyst is added, the rate of forward and reverse reactions increase equally (at the same rate)

Figure 12

Worked example

1. Consider the reversible reaction shown below, taking place in a closed reaction vessel: $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$

The concentration – time graph below represents the concentration of all reactants and products, as the reaction proceeds:



1.1 Give a reason why the reaction rates remain constant from t_1. (1)

1.2 Write down what happened at t_2. Explain the answer. (2)

1.3 Consider the changes in concentration of N_2, H_2 and NH_3 IMMEDIATELY AFTER t_2.

  1.3.1 Write down whether the concentration of each substance has INCREASED, DECREASED or REMAINED THE SAME. (3)

  1.3.2 Explain the answer in QUESTION 1.3.1, using Le Chatelier's principle. (3)

1.4 At which time (t_1, t_2 or t_3) does the system reach equilibrium for the SECOND time? (1)

1.5 Sketch a reaction – rate time graph for the forward and the reverse reaction from the start of the reaction until after the second equilibrium is established. Prove all relevant time labels.
Label the forward and reverse reaction. (3)

1.1 The reaction rates of both the forward and reverse reaction remain constant when chemical equilibrium is reached.
∴ Chemical equilibrium was established for the first time at time t_1.

1.2 There is a sharp decrease in the concentration of $NH_3(g)$ only. This indicates that the **concentration** of $NH_3(g)$ was decreased, because some $NH_3(g)$ was removed from the system, therefore the equilibrium of the system was disturbed.

1.3.1 **From the graph, the following information regarding the concentrations of the substances after t_2 can be determined:**

Concentration of H_2: Decreased.
Concentration of N_2: Decreased.
Concentration of NH_3: Increased.

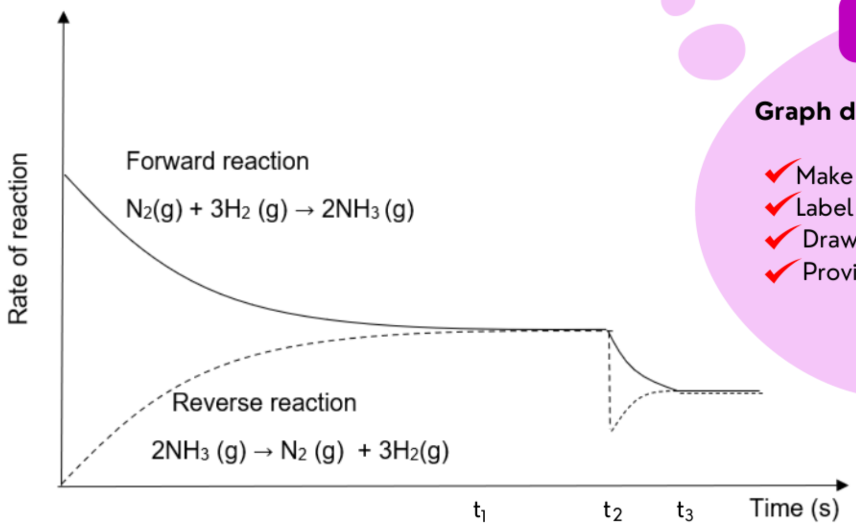
1.3.2

- Some of the NH_3(g) was removed form the system, therefore the concentration of NH_3 (g) decreased.
- According to Le Chatelier's principle, the system will respond to counteract the change by favouring the reaction that increases the concentration of NH_3 (g) i.e., the reaction that produces NH_3 (g)
- In this reaction, the forward reaction was favoured.
- Therefore the concentration of H_2 (g) and N_2(g) i.e., the reactants decreases, and the concentration of NH_3 (g) gradually increases.

1.4 From the graph determine where the rate of the forward reaction equals the rate of the reverse reaction for the second time (i.e., where the graphs flatten):
$\therefore t_3$

1.5 Some of the NH_3(g), a product, was removed from the system at equilibrium at t_2.
There will be a sharp decrease in the rate of the reverse reaction.
The rate of the forward reaction will also gradually decrease as less reactant is being produced per second, and some of the the reactant is being used up to produce more NH_3(g)
At t_3, equilibrium is re - established.

Reaction - rate time graph



PRO-TIPS

Graph drawing tips:

- ✓ Make sure the graph has a heading
- ✓ Label the axes
- ✓ Draw the graph in pencil
- ✓ Provide labels where necessary.

ACIDS AND BASES

Revision from grade 11

Acids

Properties of acids:

- Acids have a sour taste (think of the taste of lemons and vinegar)
- Acids have a pH of less than/ below 7 i.e. $0 \leq pH < 7$ (acidic)
- All acids have an H^+ ion present responsible for the acidic properties.
- Strong acids are corrosive and can eat into or burn skin.

Examples of common acids

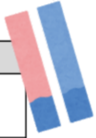
Three common examples of **strong acids** used in the laboratory:

NAME	CHEMICAL FORMULA
Hydrochloric acid	HCl
Sulphuric acid	H_2SO_4
Nitric acid	HNO_3

PRO-TIPS

Strong acids usually have a **pH greater than 0 but less than 3.**
(very low pH).
Caution must be taken when working with strong acids.

Common examples of **weak acids** used in the laboratory:



NAME	CHEMICAL FORMULA
Methanoic acid (formic acid)	HCOOH
Ethanoic acid (Acetic acid)	CH_3COOH
Carbonic acid	H_2CO_3
Phosphoric acid	H_3PO_4
Oxalic acid	$(COOH)_2$ OR $(COOH)_2 . 2H_2O$
Sulphurous acid	H_2SO_3

Acid found in vinegar

Not to be confused with sulphuric acid

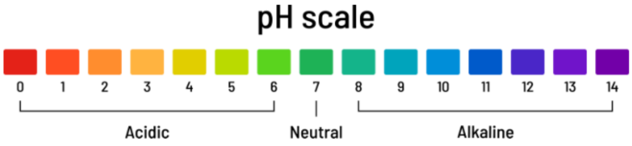
PRO-TIPS

Weak acids usually have a **pH greater than or equal to 3 but less than 7.**

Concentrated weak acids can also be corrosive.

pH scale

The pH scale is a scale of numbers from 0 to 14 used to express the acidity or alkalinity of a solution.



Bases

Properties of bases

- Bases generally feel soapy or slippery.
- Bases have a pH greater than 7 i.e. $7 < pH \leq 14$ (alkaline)
- They taste bitter (think of the taste of antacids)
- Strong bases/ strong alkalis are corrosive (like strong acids).

Examples of common bases

Common examples of **strong bases** used in the laboratory:

NAME	CHEMICAL FORMULA
Sodium hydroxide	$NaOH$
Potassium hydroxide	KOH
Lithium hydroxide	$LiOH$
Caesium hydroxide	$CsOH$
Rubidium hydroxide	$RhOH$

NOTE: All strong bases have OH^- ions present

PRO-TIPS

Strong bases usually have a **pH of between 12 and 14.** Caution must be taken when working with strong bases.

Weak bases can be classified as metal hydroxides, metal carbonates or metal bicarbonates, metal oxides and ammonia

Common examples of **weak bases** used in the laboratory:

	NAME	CHEMICAL FORMULA
	Ammonia	NH_3
Metal hydroxides	Magnesium hydroxide	$Mg(OH)_2$
	Aluminium hydroxide	$Al(OH)_3$
	Ammonium hydroxide	NH_4OH
Metal oxides	Calcium oxide	CaO
	Aluminium oxide	Al_2O_3
	Magnesium oxide	MgO
	Copper (II) oxide	CuO
Metal carbonates/metal bicarbonates	Calcium carbonate	$CaCO_3$
	Sodium carbonate	Na_2CO_3
	Sodium bicarbonate or sodium hydrogen carbonate	$NaHCO_3$
	Potassium carbonate	K_2CO_3

These metal hydroxide bases are weak bases because they are not very soluble in water i.e., they do not dissolve easily in water.

PRO-TIPS

Weak bases usually have a **pH greater than 7 but less than 12.**

Baking soda or bicarbonate of soda

PRO-TIPS

Know examples (name and chemical formula) of **all** common strong acids and bases & weak acids and bases.

Theories of acids and bases

Various scientists put forward theories to explain the properties behaviour of acids and bases.

There are two common acid - base theories, that we study in this chapter:

1. Arrhenius' theory of acids and bases
2. Lowry - Bronsted theory of acids and bases **(theory used today)**

1. Arrhenius' theory of acids and bases

The first theory explaining acid – base reactions was developed by a Swedish Chemist Svante Arrhenius.
He suggested classifying certain compounds as acids or bases based on what kind of ions formed when the compound was **dissolved in water.**
Acids and bases can be defined as follows, according to Arrhenius' theory:

Definition: Acid (according to Arrhenius' theory): An acid is a substance that produces hydrogen ions (H^+) or Hydronium ions (H_3O^+) when it dissolves in water.

NOTE: A **hydronium ion** (H_3O^+) is also called an **oxonium ion**.

Remember an ion has a charge - when writing the name of an ion, the word **ion must always follow after the name.**

Definition: base (according to Arrhenius' theory): A base is a substance that produces hydroxide ions (OH^-) when it dissolves in water.

There were shortcomings to Arrhenius's theory:

- Limits acids and bases to reactions occurring in aqueous solutions, hence it could not explain reactions that occurred in solvents other than water.
- This theory cannot be applied to all acids and bases, for example: NH_3,Na_2CO_3 etc. which have no OH^- in the molecule.

NOTE: A hydrogen atom has an atomic number (number of protons) of 1 and a mass number of 1 (number of protons and neutrons), therefore a neutral hydrogen atoms has 1 proton and 1 electron (0 neutrons). If a hydrogen atom loses an electron, it only has a proton. Therefore, a hydrogen ion is a proton.

2. Lowry - Bronsted theory of acids and bases

These shortcomings were cleared by a theory which was proposed independently (and simultaneously) by Thomas Martin Lowry in England and Johannes Bronsted in Denmark in 1923, known as the Lowry- Bronsted theory of acids and bases. The Lowry - Bronsted theory is the acid - base theory used today.

According to the Lowry- Bronsted theory of acids and bases, acids and bases involve the transfer of protons (H^+ ions)

Definition: Acid (according to Lowry- Bronsted theory): An acid is proton (H^+ ion) donor.
Definition: Base (according to Lowry- Bronsted theory): A base is proton (H^+ ion) acceptor.

Condition: Bronsted and Lowry stated that for an acid to be a proton donor, there must be a base to accept protons from it. It can be concluded that acids and bases always react together. The reaction between an acid and a base, is a proton transfer reaction/ involves the transfer of protons known as **protolysis.**

Acid - base reactions: Conjugate acid - base pairs

- Acid - base reactions **involve the transfer of protons (H^+ ions).** However, in order for an acid to donate a H^+ ion, there must be a base present to accept it.

- When an acid donates a proton (H^+) a **conjugate base** is formed. The acid and the conjugate base are called a **conjugate acid – base pair**.

Example: hydrogen chloride reacts with ammonia. The balanced equation for the reaction:

$$HCl\,(g) + NH_3\,(g) \rightleftharpoons Cl^-\,(aq) + NH_4^+\,(aq)$$

NOTE: Most acid - base reactions are reversible reactions.

① **Analysis:** HCl (an acid) donates a proton (H^+ ion), it forms Cl^- ions. This can be written as a reaction:

$$\underset{\substack{\text{acid}\\ \text{Strong acid}}}{HCl} \rightleftharpoons H^+ + \underset{\substack{\text{Conjugate base}\\ \text{Weak conjugate base}}}{Cl^-}$$

PRO - TIPS

- If the acid is a strong acid, its conjugate base is a weak base.
- If the base is a strong base, its conjugate acid is a weak acid.

- In the forward reaction, when HCl donates a H^+, it forms Cl^-. Cl^- can accept H^+ in the reverse reaction (and act as a **base**) to form HCl.
- HCl and Cl^- are **conjugate acid - base pairs** and are substances that differ by one hydrogen ion in their formulae.

$$\underset{\substack{\text{base}\\ \text{Weak base}}}{NH_3} + H^+ \rightleftharpoons \underset{\substack{\text{conjugate acid}\\ \text{Strong conjugate acid}}}{NH_4^+}$$

② **Analysis:** NH_3(a base) can accept a H^+ion (from HCl) to form NH_4^+.This can be written as a reaction:

- In the forward reaction, NH_3 accepts a H^+ from HCl, to form NH_4^+ and therefore NH_3 acts as a base.
- In the reverse reaction, NH_4^+ is able to donate a H^+ to form NH_3, therefore it acts as an acid.
- NH_3 and NH_4^+ differ by one H^+ ion in their formulae and are **conjugate acid - base pairs.**

Conclusions

- ✓ Conjugate acid - base pairs are substances that differ by ONE H^+ ion in their formulae only.
- ✓ The conjugate acid has **one additional H^+ ion** in its formulae compared to the base.
- ✓ The conjugate base has **one less H^+ ion** in its formulae compared to the acid.

From example:

$$\underset{\text{Acid 1}}{HCl\,(g)} + \underset{\text{base 2}}{NH_3\,(g)} \rightleftharpoons \underset{\text{Conjugate base 1}}{Cl^-\,(aq)} + \underset{\text{Conjugate acid 2}}{NH_4^+\,(aq)}$$

Conjugate acid - base pairs in this reaction:

1. HCl and Cl^-
2. NH_3 and NH_4^+

Worked example

Multiple choice questions

1. Consider the chemical reaction shown below:

$$CH_3COOH(aq) + H_2O(l) \rightleftharpoons CH_3COO^-(aq) + H_3O^+(aq)$$

Which ONE of the following represents a conjugate acid - base pair?

A H_2O and CH_3COOH

B CH_3COOH and CH_3COO^-

C CH_3COOH and H_3O^+

D H_2O and CH_3COO^-

Answer: B

Conjugate acid base pairs always differ by one H^+ ion in their formulae.
From the reaction,

$$\underbrace{CH_3COOH(aq)}_{\text{acid 1}} + \underbrace{H_2O(l)}_{\text{base 2}} \rightleftharpoons \underbrace{CH_3COO^-(aq)}_{\text{Conjugate base 1}} + \underbrace{H_3O^+(aq)}_{\text{Conjugate acid 2}}$$

Ethanoic acid is a common weak acid
Ethanoic acid can donate one H^+ ion (proton)

2. Which ONE of the following represents the conjugate acid of NO_3^- ?

A Nitrogen dioxide

B Hydrogen nitrite

C Nitric acid

D Nitrous acid

Answer: C

The conjugate acid has one additional H^+ ion:
The reaction: $\underbrace{NO_3^-}_{\text{base}} + H^+ \rightleftharpoons \underbrace{HNO_3}_{\text{Conjugate acid}}$

The conjugate acid is nitric acid, a **strong acid**.

Monoprotic acids & polyprotic acids

Acids can be classified as monoprotic acids or polyprotic acids (i.e., diprotic or triprotic acids) depending on how any protons (H^+) ions the acid is able to donate.

Monoprotic acids

Acid that **can donate** only ONE proton (H^+).

Examples of monoprotic acids:

HCl: Hydrochloric acid
HNO_3 : nitric acid
CH_3COOH : Ethanoic acid (acetic acid)

Strong covalent bond

Ethanoic acid is only able to donate this one H^+

Polyprotic acids

Remember: 'poly' means 'many'. Polyprotic acids can donate more than one proton (H^+)

Diprotic acids

(di = two)

Acid that **can donate** TWO protons (H^+).

Examples of diprotic acids:

H_2SO_4 :sulphuric acid
H_2CO_3 :carbonic acid

Triprotic acids

(tri = three)

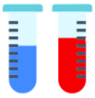
Acid that **can donate** THREE protons (H^+).

Examples of triprotic acids:

H_3PO_4 :phosphoric acid

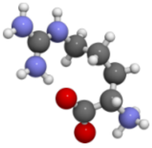
Ampholytes

Certain substances can act as an acid in one reaction, and a base in another reaction. These substances are called **ampholytes** or **amphiprotic substances.**



Definition: **Ampholyte**: Substance that can act as either an acid or a base.

Did you know?
Amino acids(molecules that combine to form proteins) are ampholytes!



Common examples of ampholytes:

Remember: According to the Lowry - Bronsted theory:

- An acid is a proton (H^+ ion) donor.
- A base is a proton (H^+ ion) acceptor.

Example of ampholyte	Substance acting as an acid	Substance acting as a base
H_2O (water)	$H_2O \rightleftharpoons H^+ + OH^-$	$H_2O + H^+ \rightleftharpoons H_3O^+$
HSO_4^- (hydrogen sulphate ion)	$HSO_4^- \rightleftharpoons H^+ + SO_4^{2-}$	$HSO_4^- + H^+ \rightleftharpoons H_2SO_4$
HCO_3^- (hydrogen carbonate ion)	$HCO_3^- \rightleftharpoons H^+ + CO_3^{2-}$	$HCO_3^- + H^+ \rightleftharpoons H_2CO_3$
$H_2PO_4^-$ (dihydrogen phosphate ion)	$H_2PO_4^- \rightleftharpoons H^+ + HPO_4^{2-}$	$H_2PO_4^- + H^+ \rightleftharpoons H_3PO_4$
HPO_4^{2-} (hydrogen phosphate ion)	$HPO_4^{2-} \rightleftharpoons H^+ + PO_4^{3-}$	$HPO_4^{2-} + H^+ \rightleftharpoons H_2PO_4^-$

Water is a very common example of an ampholyte - it can donate a H^+ to form a OH^- and it can accept a H^+ to form H_3O^+ through a dative covalent bond.

HSO_4^- is the conjugate base of H_2SO_4

HCO_3^- is the conjugate base of H_2CO_3

$H_2PO_4^-$ is the conjugate base of H_3PO_4

HPO_4^{2-} is the conjugate base of $H_2PO_4^-$

PRO-TIPS

Examples of ampholytes include water and the conjugate base of diprotic and triprotic acids.

Worked example

C + A

Multiple choice question

1. HPO_4^{2-} can act as an ampholyte. In which ONE of the following reactions does HPO_4^{2-} act as a Lowry- Bronsted acid?

A $HPO_4^{2-} + H^+ \rightleftharpoons H_2PO_4^-$

B $HPO_4^{2-} + HPO_4^{2-} \rightleftharpoons 2HPO_4^{2-}$

C $HPO_4^{2-} + H_2O \rightleftharpoons H_2PO_4^- + OH^-$

D $HPO_4^{2-} + H_2O \rightleftharpoons PO_4^{3-} + H_3O^+$

Answer: D

An acid (according to Lowry- Bronsted theory) is a proton (H^+) **donor**. When HPO_4^{2-} donates a proton (H^+) it forms PO_4^{3-}. This matches the reaction represented in option **D**.

Worked example

C + A

1. Consider the following reaction: $H_2O + HXO_4^- \rightleftharpoons XO_4^{2-} + H_3O^+$

1.1 What is an amphiprotic substance? (2)

1.2 Which two substances in the above equation can act as ampholytes? Explain the answer. (3)

1.1 **NOTE:** An amphiprotic substance is an ampholyte. This question is asking the definition of an ampholyte or amphiprotic substance.

Amphiprotic substance: Substance that can act as either an acid or a base.

1.2 **Tip:** An ampholyte must have at least one hydrogen ion (to donate to act as a acid) and it must be able to accept a H^+ (to act as a base). In most cases, this is a negatively charged ion, but it can also be a neutral molecule (for example H_2O).

$$H_2O + HXO_4^- \rightleftharpoons XO_4^{2-} + H_3O^+$$

- Can accept and donate H^+ ✓
- Can accept and donate H^+ ✓
- Can accept H^+ only, but no H^+ available to donate ✗
- Can donate H^+ but cannot accept H^+ ✗

Answer: H_2O and HXO_4^-

H_2O and HXO_4^- have a H^+ available to donate, and both these substances are also able to accept a H^+.

ACID-BASE REACTIONS: NEUTRALISATION REACTIONS

In a neutralisation reaction, an acid reacts with a base according to the correct stoichiometric mole ratios from the balanced reaction. All the moles of acid reacts completely with all the moles of base. Generally, in a neutralisation reaction a **salt and water** is produced.

General equation for a neutralisation reaction:

Acid + base ⟶ salt + water

PRO-TIPS

In a neutralisation reaction,
the pH of the final solution (containing the salt) is not necessarily 7.
The strength of the acid and base that reacts determines the pH of the final solution:

- Strong acid + strong base **pH = 7**
- Weak acid + weak base **pH = 7**
- Strong acid + weak base **pH < 7**
- Weak acid + strong base **pH > 7**

If the base is a metal carbonate base or a metal bicarbonate base, carbon dioxide (CO_2) is produced as a byproduct:

Acid + base ⟶ salt + water + carbon dioxide

NOTE: Most neutralisation reactions are **not** reversible reactions.
When writing a reaction, always balance the reaction.

- An acid – base reaction is an example of an **ion - exchange reactions**.
- In an ion exchange reaction the positive ion of the one reactant bonds to the negative ion of the other reactant.
- An acid- base reaction involves the transfer of protons (H^+ ions).

Example: Complete the following reaction: $HCl\,(aq) + NaOH\,(aq) \rightarrow$

Ion - exchange reaction:

Acid Base Salt Water

$HCl\,(aq) + NaOH\,(aq) \rightarrow NaCl\,(aq) + H_2O(l)$ ✓ **Balanced**

H^+ Cl^- Na^+ OH^-

[redacted]

Na^+ Cl^- bond
in a ratio 1: 1
to form a neutral compound with a net charge 0

Worked example

C + A

1. Consider the incomplete reaction **I** and **II** shown below:

Reaction **I**: $HNO_3(aq) + Na_2CO_3(aq)$
Reaction **II**: $HNO_3(aq) + KOH(aq)$

1.1 Write down a balanced reaction for reaction **I** and write down the name of the salt produced in reaction **I**. (4)

1.2 In which reaction (**I** or **II**) is carbon dioxide produced? (1)

1.3 Is the salt produced in reaction **II** ACIDIC, BASIC or NEUTRAL?. (1)

1.1 In reaction **I**, the base is a metal carbonate base, therefore carbon dioxide gas is produced as a by product:

Ion - exchange reaction:

Acid | Metal carbonate base | Salt | Water | carbon dioxide

$2HNO_3(aq) + Na_2CO_3(aq) \rightarrow 2NaNO_3(aq) + H_2O(l) + CO_2(g)$ ✓ **Balanced**

H^+ NO_3^- $2Na^+$ CO_3^{2-}

[redacted]

Na^+ NO_3^- bond in a ratio 1: 1 m a neutral compound with a net charge 0

Byproduct produced when the base is a metal carbonate base

∴ **Name of salt:** sodium nitrate

1.2 Write a balanced reaction for reaction **II**, as evidence that because the base is not a metal carbonate, carbon dioxide will not be produced.

Ion - exchange reaction:

Acid | Base | Salt | Water

Reaction **II**: $HNO_3(aq) + KOH(aq) \rightarrow KNO_3(aq) + H_2O(l)$ ✓ **Balanced; no carbon dioxide produced**

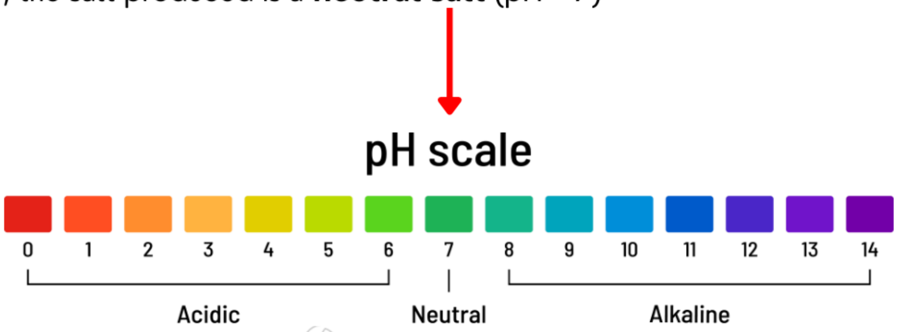
H^+ NO_3^- K^+ OH^-

[redacted]

K^+ NO_3^- bond in a ratio 1: 1 to form a neutral compound with a net charge 0

∴Carbon dioxide is only produced in reaction **I**, as the base is a metal carbonate base.

1.3 Note the strength of the acid and base that reacted to produce the salt in reaction **II**:
HNO_3: strong acid
KOH: strong base
Therefore, the salt produced is a **neutral salt** (pH = 7)



ACID – BASE TITRATIONS: NEUTRALISATION REACTIONS CONTINUED

Through the process of an **acid - base titration**, where an acid and base completely neutralise each other, the **unknown concentration** of an acid **or** a base can be determined.

Acid - base titration: process

To determine the unknown concentration of an acid or base, a solution of known concentration (acid or base) must be reacted against this solution of unknown concentration. A solution of known concentration is called a **standard solution**.

Standard solution: Solution of which the concentration is exactly known.

1. How to prepare a standard solution

Example:

Aim: To prepare a 250 cm^3 NaOH solution with a concentration of 0,5 mol.dm^{-3}

Apparatus:

- Electronic scale (balance)
- Watch glass/ petri dish
- Funnel
- Volumetric flask with stopper
- Wash bottle

Method:

1. Calculate the mass of NaOH (s) needed, using stoichiometric calculations.
2. Measure the correct amount of solute accurately in a watch glass or a petri dish on a scale.
3. Use a funnel to carefully pour it into a volumetric flask. Rinse off the last bit of substance from the watch glass using a wash bottle with distilled water.
4. First add a little distilled water (solvent), put the stopper on the flask and swirl the flask to dissolve the substance.
5. Carefully add more water, exactly up to the correct volume mark (the bottom of the meniscus).
6. Mark the flask with a label (e.g., 0,5 mol.dm^{-3} NaOH)

2. Conducting the acid - base titration

Apparatus needed to conduct a titration:

- Burette

- Burette clamp

- Conical or Erlenmeyer flask

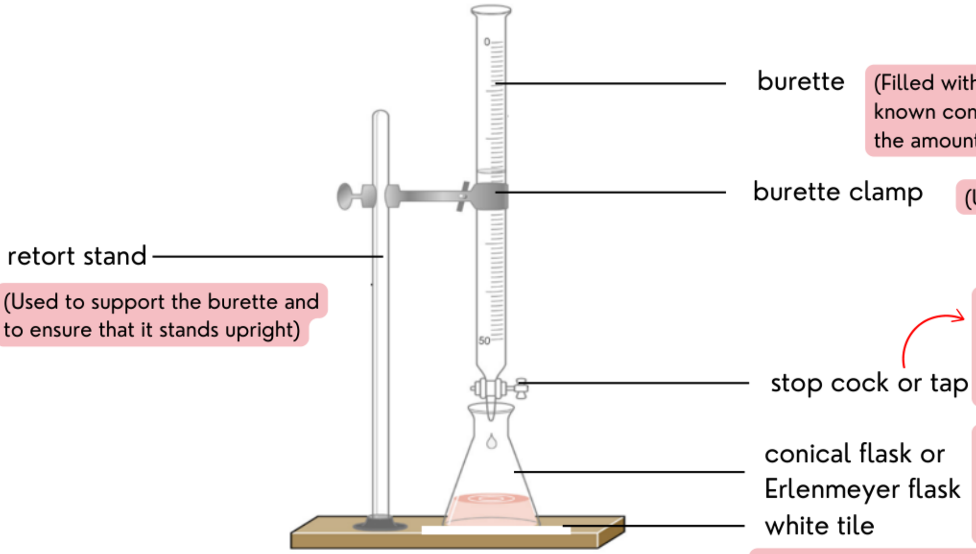
- Retort stand

- White tile

Safety precautions when conducting a titration

- Wear gloves when working with corrosive acids and bases.
- Wear safety glasses or safety goggles.
- Wear closed shoes.
- Wear a lab coat to protect your skin and clothing.

Set up of the apparatus for a titration and the functions of the apparatus



(Filled with the standard solution of known concentration; used to measure the amount of standard solution used)

(Used to secure the burette)

(Used to support the burette and to ensure that it stands upright)

(Used to control the amount of standard solution from the burette that enters the conical or Erlenmeyer flask)

(Contains the solution of **unknown** concentration and a few drops of a suitable indicator)

(Used to see the colour changes more easily)

Method

- Prepare a standard solution of known concentration of acid **or** base.
- Place the standard solution of known concentration carefully in the burette to the correct volume (0 ml), make sure that the bottom of the meniscus is on the line.
- This standard solution is titrated against a solution of acid/ base of **unknown concentration**. The solution of unknown concentration is placed in the conical flask or Erlenmeyer flask.
- Add a few drops of indicator (3 – 5 drops) to the solution of unknown concentration in the conical flask or Erlenmeyer flask. The indicator will change colour when the **endpoint** (of the titration) is reached.
- **To ensure reliability and accuracy of results, repeat the titration three times.**

Results

Through a neutralisation reaction, the unknown concentration of an acid or base can be determined. The indicator indicates the end point of the titration. The **end point**, if the titration is accurately conducted, usually also indicates the **equivalence point** of a titration.

End point vs equivalence point

Endpoint of a titration: is the point where the indicator changes colour.

Equivalence point of a titration: is the point at which the acid/base has completely reacted with the base/acid.
An indicator is used to show the endpoint of a titration by a (sharp) colour change.

Indicators

Indicators are dyes that change colour at a specific pH value. An indicator is used to determine the point of neutralisation (equivalence point), when it indicates the **endpoint** in a titration. Indicators are usually weak acids and bases.

NOTE: When the equivalence point (point of neutralisation) has been reached, the number of moles of acid has completely reacted with the number of moles of base, there is neither moles of acid nor moles of the base in excess.

Choosing the correct indictor to indicate the end point of a titration

The pH of the solution at the end point depends on the strength of the acid or base being used. The correct indicator must be chosen so that the pH of the endpoint falls within the transition range of the indicator. The following guideline can be used:

Name of indicator	Used in titration with	Colour in acid	Colour in base	Colour when end point reached	pH range	pH of solution	End point
Methyl orange	Strong acid, Weak base	Red	Yellow	Orange - red	3,1 – 4,4	< 7	≈3,7
Bromothymol Blue	Strong acid, Strong base **OR** Weak acid, Weak base	Yellow	Blue	Green	6,0 – 7,6	= 7	≈7
Phenolphthalein	Weak acid, Strong base	**Colourless (clear)**	Pink (dark pink/ magenta/ fuchsia)	Rose/light pink	8, 3 - 10, 0	> 7	≈9,3

Titration calculations

Calculating the unknown concentration of an acid or base

In a neutralisation reaction, the following stoichiometric formula can be used to determine the unknown concentration of an acid/ base:

Number of moles of acid reacted ←

Number of moles of base reacted ←

$$\frac{c_aV_a}{c_bV_b} = \frac{n_a}{n_b}$$

NOTE: This formula can only be used if the acid neutralises the base; i.e., if all the moles of acid reacts with all the moles of base, according to the correct mole ratios

What do these variables mean and what are the SI units?

c_a = concentration of the acid in $mol.dm^{-3}$

V_a = volume of the acid in dm^3

c_b = concentration of the base in $mol.dm^{-3}$

V_b = volume of the base in dm^3

n_a = number of moles of acid from the **balanced** acid - base reaction

n_b = number of moles of base from the **balanced** acid - base reaction

PRO – TIPS

Volume conversion chart

$cm^3 \rightarrow dm^3$	÷ 1000
$m^3 \rightarrow dm^3$	× 1000
$ml \rightarrow dm^3$	÷ 1000

NOTE: 1 ml = 1 cm^3

1 litre = 1000 ml = 1 dm^3

OR

Use stoichiometric formulae and mole ratios from the balanced acid - base reaction:

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

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

OR

$$n = cV$$

$$c = \frac{m}{MV}$$

Worked example

C + A

1. 25 cm^3 of 0,1 $mol.dm^{-3}$ KOH is exactly neutralised by 36 cm^3 of HCl. The balanced equation for the reaction is:

$$HCl\,(aq) + KOH(aq) \rightarrow KCl\,(aq) + H_2O\,(l)$$

1.1 Write down a suitable indicator for this titration. Give a reason for the answer. (2)

1.2 Calculate the concentration of the HCl solution. (4)

1.3 Calculate the mass of the salt produced. (3)

1.1 To determine which indicator to use to indicate the end point of titration, determine the strength of the acid and base reacting. Explain the answer in terms of the strength of the acid and base reacting, unless stated otherwise.
HCl: Strong acid
KOH: Strong base
∴ Bromothymol blue. A strong acid is being titrated against a strong base.

1.2 **OPTION 1**

- The concentration and volume of the base (KOH) neutralised is known, this can be used to calculate the number of moles of KOH used up/ neutralised.
- Using the mole ratios from the balanced equation, the number of moles of HCl used up/neutralised can be determined.
- The concentration of HCl (acid) can be determined as the volume neutralised is known.

OR

OPTION 2

- The base completely neutralises the acid, therefore the formula $\frac{c_aV_a}{c_bV_b} = \frac{n_a}{n_b}$ can be used to determined the concentration of HCl (acid)

OPTION 1

n(KOH used up/neutralised) = cV
n(KOH used up/neutralised) = (0,1)(0,025)
n(KOH used up/neutralised) = 2,5 x 10^{-3} mol

n (HCl used up/ neutralised) = n (KOH used up/neutralised) = 2,5 x 10^{-3} mol

c (HCl) = $\frac{n}{V}$

c (HCl) = $\frac{(2,5 \times 10^{-3})}{(0,036)}$

c(HCl) = 0,069 $mol.dm^{-3}$

OR

OPTION 2

$$\frac{c_aV_a}{c_bV_b} = \frac{n_a}{n_b}$$

$$\frac{c_a(0,036)}{(0,1)(0,025)} = \frac{(1)}{(1)}$$

$$c_a = \frac{(0,1)(0,025)}{(0,036)}$$

c_a = 0,069 $mol.dm^{-3}$

Tip: Round off answers to three decimals places if 0,0..
OR
Write the answer in scientific notation.

1.3 **OPTION 1**

n(KCl produced) = n (KOH used up) = $2{,}5 \times 10^{-3}$ mol

n(KCl produced) = $\frac{m}{M}$

$(2{,}5 \times 10^{-3}) = \frac{m}{(74{,}5)}$

M(KCl) = 39 + 35,5
M(KCl) = 74,5 g.mol^{-1}

m(KCl produced) =0,19 g

OR

OPTION 2

n(KOH used up/neutralised) = cV
n(KOH used up/neutralised) = (0,1)(0,025)
n(KOH used up/neutralised) = $2{,}5 \times 10^{-3}$ mol

n(KCl produced) = n (KOH used up) = $2{,}5 \times 10^{-3}$ mol

n(KCl produced) = $\frac{m}{M}$

M(KCl) = 39 + 35,5
M(KCl) = 74,5 g.mol^{-1}

$(2{,}5 \times 10^{-3}) = \frac{m}{(74{,}5)}$

m(KCl produced) =0,19 g

Worked example

A + P

2. 2,87 g of potassium hydroxide is dissolved in 250 cm^3 distilled water.

2.1 Calculate the concentration of the solution. (3)

75 cm^3 of the potassium hydroxide solution is diluted to a solution of 200 cm^3 solution.

2.2 Calculate the concentration of the diluted solution of potassium hydroxide (4)

28,8 cm^3 of the KOH solution is used to neutralise the sulphuric acid, according to the following reaction: $2KOH (aq) + H_2SO_4 (aq) \rightarrow K_2SO_4(aq) + 2H_2O (l)$
Consider the table of information shown below:

Name of indicator	End point
Methyl orange	3,7
Bromothymol Blue	7
Phenolphthalein	9,3

2.3 Write down the name of a suitable indicator used in this titration.
Give a reason for the answer by referring to the information in the table. (2)

2.4 Calculate the mass of H_2SO_4 that was neutralised. (6)

2.1 **OPTION 1**

The mass of the KOH solute and the volume of solvent is known. To determine the concentration of the solution, the number of moles of solute must first be determined. The concentration of the solution can be calculated using the formula: **c =** $\frac{n}{V}$

OR

OPTION 2

The mass of the KOH solute and the volume of solvent is known. The formula **c =** $\frac{m}{MV}$ can directly be used to determine the concentration of the solution.

OPTION 1

n(KOH) = $\frac{m}{M}$

n(KOH) = $\frac{(2{,}87)}{(56)}$

M(KOH) = 39 + 16 + 1
M(KOH) = 56 g.mol^{-1}

n(KOH) = 0,051… mol

c (KOH) = $\frac{n}{V}$

c (KOH) = $\frac{(0{,}051\ldots)}{(0{,}25)}$

c(KOH) = 0,205 mol.dm^{-3}

OR

Remember: keep the answer in your calculator Press ‘Ans’ button to retrieve answer

OPTION 2

c = $\frac{m}{MV}$

M(KOH) = 39 + 16 + 1
M(KOH) = 56 g.mol^{-1}

c = $\frac{(2{,}87)}{(56)(0{,}25)}$

c = 0,205 mol.dm^{-3}

2.2 OPTION 1

A 250 cm^3 solution of KOH was prepared, however, only a portion of this volume (75 cm^3) was diluted.

The concentration of a portion of the volume is the same as the concentration of the total volume, as the ratio of the number of moles of solute to the volume of solvent remains constant.

The number of moles in 75 cm^3 of the solution can be determined using the formula: **$c = \frac{n}{V}$**

The new diluted solution will contain the same number of moles as the 75 cm^3 solution, using the concentration formula (**$c = \frac{n}{V}$**), the new concentration of the dilute solution can be determined.

OPTION 2

A 250 cm^3 solution of KOH was prepared, however, only a portion of this volume (75 cm^3) was diluted.

The concentration of a portion of the volume is the same as the concentration of the total volume, as the ratio of the number of moles of solute to the volume of solvent remains constant. The dilution formula $c_1V_1 = c_2V_2$ can be used to determine the concentration of the dilute solution.

OPTION 1

c (75 cm^3 KOH solution) = $\frac{n}{V}$

$(0,205) = \frac{n}{(0,075)}$

n (75 cm^3 KOH solution) = (0,205)(0,075)

n (75 cm^3 KOH solution) = 0,0153… mol

n(200 cm^3 KOH solution) = n (75 cm^3 KOH solution) = 0,0153… mol

c (200 cm^3 KOH solution) = $\frac{n}{V}$

c (200 cm^3 KOH solution) = $\frac{(0,0153…)}{(0,2)}$

c (200 cm^3 KOH solution) = 0,077 $mol.dm^{-3}$

OR

OPTION 2

$c_1V_1 = c_2V_2$

$(0,205)(0,075) = c_2(0,2)$

$c_2 = \frac{(0,205)(0,075)}{(0,2)}$

$c_2 = 0,077\ mol.dm^{-3}$

2.3 The information in the table must be referenced, therefore the answer must be explained in terms of the end point. Remember that a strong acid is being titrated against a strong base.

∴ Bromothymol blue. The end point (pH = 7) is the approximate end point when a strong acid is titrated against a strong base.

2.4

A 200 cm^3 solution of KOH was prepared, however, only a portion of this volume (28,8 cm^3) was used.The concentration of a portion of the volume is the same as the concentration of the total volume, as the ratio of the number of moles of solute to the volume of solvent remains constant.

The number of moles of KOH neutralised can be determined by using the formula $n = cV$.

Using mole ratios from the balanced reaction, the number of moles of H_2SO_4 neutralised can be determined.

The number of moles of H_2SO_4 neutralised can be converted into mass using the formula: $n = \frac{m}{M}$

c (28,8 cm^3 KOH solution) = $\frac{n}{V}$

$(0,077) = \frac{n}{(0,0288)}$

n (28,8 cm^3 KOH solution) = (0,077)(0,0288)

n (28,8 cm^3 KOH solution) = 2,2176 x 10^{-3} mol

n(KOH neutralised/used up) = 2,2176 x 10^{-3} mol

n(KOH neutralised/used up) : n (H_2SO_4 neutralised/used up)

2 mol : 1 mol

n(H_2SO_4 neutralised/used up) = $\frac{1}{2}n$(KOH neutralised/used up)

n(H_2SO_4 neutralised/used up) = $\frac{1}{2}$(2,2176 x 10^{-3})

n(H_2SO_4 neutralised/used up) = 1,1088 x 10^{-3} mol

Mass of H_2SO_4 neutralised/used up

n(H_2SO_4 neutralised/used up) = $\frac{m}{M}$

(1,1088 x 10^{-3}) = $\frac{m}{(98)}$

$M(H_2SO_4) = 2(1) + 32 + 4(16)$

$M(H_2SO_4) = 98\ g.mol^{-1}$

m(H_2SO_4 neutralised/used up) = 0,109 g (or 0,11 g)

STRONG AND WEAK ACIDS AND BASES

Strong acids vs weak acids

Acids are covalently bonded molecules and can be classified as strong or weak acids based on their ability to **ionise** in an aqueous solution such as water.

Ionisation is a process that takes place when a covalently bonded compound reacts with water to form new ions.

Remember: Water is necessary for ionisation to take place

	STRONG ACIDS	WEAK ACIDS
Definition (Based on its ability to ionise and donate H^+)	**Definition:** Strong acids ionise completely in water to form a high concentration of H_3O^+ ions. **Example**: $\underset{\text{Acid}}{HCl} + \underset{\text{Base}}{H_2O} \rightleftharpoons H_3O^+ + Cl^-$ **Conclusion:** There is a higher concentration of ions, namely H_3O^+ ions and Cl^- ions in solution than molecules.	**Definition:** Weak acids ionise incompletely in water to form a high concentration of H_3O^+ ions. **Example**: $\underset{\text{Acid}}{CH_3COOH} + \underset{\text{Base}}{H_2O} \rightleftharpoons H_3O^+ + CH_3COO^-$ **Conclusion:** There is a higher concentration of molecules than ions (H_3O^+ and CH_3COO^-) in solution
pH range	pH greater than or equal to 0 but less than 3	pH greater than 3 but less than 7
Conductivity	A strong acid conducts electricity better than a weak acid because it ionises completely and therefore forms more ions in solution.	A weak acid is a weaker conductor of electricity than a strong acid because it ionises incompletely (partially) and therefore forms fewer ions in solution.
Reaction rate (at a constant temperature)	Strong acids have a faster reaction rate than weak acids, because they ionise completely and readily. **Example:** When a strong acid e.g., HCl is reacted with Mg, $H_2(g)$ is produced at a faster rate compared to if a weak acid of the same concentration is used.	Weak acids have a slower reaction rate than strong acids, because they only partially ionise. **Example:** When a weak acid e.g., CH_3COOH is reacted with Mg, $H_2(g)$ is produced at a slower rate compared to if a strong acid of the same concentration is used.

Strong bases vs weak bases

Most bases are ionic compounds, except for ammonia (NH_3) which is a covalently bonded molecule.

Bases are classified as strong or weak according to their ability to dissociate or ionise (in the case of ammonia) in an aqueous solution such as water.

Dissociation: A process that takes place when an ionic compound dissolves in water, separating the substance into its component ions.

PRO - TIPS

The conductivity of a solution depends on the concentration of ions in solution.

Strong bases

Examples of strong bases: NaOH (sodium hydroxide), KOH (potassium hydroxide), LiOH (lithium hydroxide).

Definition: Strong base: Strong bases dissociate completely in water to form a high concentration of OH^- ions.

Example: NaOH dissociates in water.

Remember: Water is necessary for dissociation to take place

$$NaOH\ (s) \overset{H_2O}{\rightleftharpoons} Na^+(aq) + OH^-(aq)$$

When a strong base, for example, sodium hydroxide (NaOH) is dissolved in water, it dissociates completely to form a high concentration of Na^+ and OH^- ions in solution, resulting in the solution containing higher concentrations of positive and negative ions, with very few NaOH molecules remaining.

Weak bases

Examples of weak bases: Ammonia (NH_3), sodium bicarbonate/ sodium hydrogen carbonate ($NaHCO_3$), magnesium hydroxide ($Mg(OH)_2$), calcium oxide (CaO)

Definition: Weak base: Weak bases ionise/dissociate incompletely in water to form a low concentration of OH^- ions.

Example: NH_3 ionises in water.

Remember: Water is necessary for ionisation to take place

$$\underset{\text{Base}}{NH_3(g)} + \underset{\text{Acid}}{H_2O\ (l)} \rightleftharpoons NH_4^+(aq) + OH^-\ (aq)$$

CONCENTRATED AND DILUTE ACIDS AND BASES

The concentration of a solution is the ratio of the number of moles of solute to the volume of solvent. A concentrated solution has more moles of solute per unit volume than a dilute solution, as shown in figure 1 below.

Concentrated solution **Dilute solution**

figure 1

NOTE:
Strong and weak acids can be concentrated or diluted, but this does not change the strength of the acid or base. It is possible to have a dilute, strong acid/base or a concentrated weak acid/ base.

The table below represents the concentrations and strengths of HCl and KOH

SOLUTION	STRENGTH
HCl (1 $mol.dm^{-1}$)	Strong acid
HCl (0,1 $mol.dm^{-1}$)	Strong acid
KOH (1 $mol.dm^{-1}$)	Strong base
KOH (0,1 $mol.dm^{-1}$)	Strong base

The concentration of an acid/base does not affect its strength.

Definitions:

Concentrated acids: contain a large amount (number of moles) of acid in proportion to the volume of water.

Concentrated bases: contain a large amount (number of moles) of base in proportion to the volume of water.

Dilute acids: contain a small amount (number of moles) of acid in proportion to the volume of water.

Dilute bases: contain a small amount (number of moles) of base in proportion to the volume of water.

EQUILIBRIUM (IONISATION) CONSTANTS FOR ACIDS (K_A) AND BASES (K_B)

The acid ionisation constant (K_a)

When an acid (**HA**) is dissolved in water, it ionises according to the following general equation (**NOTE:** water acts as the base in this reaction):

$$\underset{\text{acid 1}}{HA\,(aq)} + \underset{\text{base 2}}{H_2O\,(l)} \rightleftharpoons \underset{\text{Conjugate acid 2}}{H_3O^+(aq)} + \underset{\text{Conjugate base 1}}{A^-(aq)}$$

The equilibrium constant i.e. the ionisation constant for an acid (K_a):

$$K_a = \frac{[\text{products}]}{[\text{reactants}]}$$

$$K_a = \frac{[H_3O^+][A^-]}{[HA]}$$

assume $[H_2O] = 1$

Remember: [ ] = concentration

- The K_a value (equilibrium constant for an acid) (which is a constant at constant temperature) indicates whether it is a strong or weak acid, i.e., how readily it will donate protons.
- A strong acid has large values for the $[H_3O^+]$ and $[A^-]$ and a small value of [HA] (the acid).
- If $K_a > 1$, this indicates that [products] > [reactants], this indicates a larger degree of ionisation and that this is a **strong acid**.
- If $K_a < 1$, this indicates that [products] < [reactants], this indicates a smaller degree of ionisation and that this is a **weak acid**.
- **The larger the K_a value is, the stronger the acid, the smaller the K_a value, the weaker the acid.**

The base ionisation constant (K_b)

When a base (**B**), for example, ammonia is dissolved in water, it ionises according to the following general equation:(**NOTE:** water acts as the acid in this reaction):

$$\underset{\text{base 1}}{B\,(g)} + \underset{\text{acid 2}}{H_2O\,(l)} \rightleftharpoons \underset{\text{Conjugate base 1}}{OH^-(aq)} + \underset{\text{Conjugate acid 2}}{BH^+(aq)}$$

The equilibrium constant i.e. the ionisation constant for a base (K_b):

$$K_b = \frac{[\text{products}]}{[\text{reactants}]}$$

$$K_b = \frac{[BH^+][OH^-]}{[B]}$$

assume $[H_2O] = 1$

- The K_b value (equilibrium constant for an base) (which is a constant at constant temperature) indicates whether it is a strong or weak base, i.e., how readily it will accept protons.
- A strong base has large values for the $[OH^-]$ and $[BH^+]$ and a small value of [B] (the base).
- If $K_b > 1$, this indicates that [products] > [reactants], this indicates a larger degree of ionisation/dissociation and that this is a **strong base**.
- If $K_b < 1$, this indicates that [products] < [reactants], this indicates a smaller degree of ionisation/dissociation and that this is a **weak base**.
- **The larger the K_b value is, the stronger the base, the smaller the K_b value, the weaker the base.**

Worked example

Multiple choice question

1. The acid ionisation constant Ka for the ionisation of each of the following acids in water at 25°C is given in the table below.

Acid	K_a
H_2X	$2{,}8 \times 10^{-3}$
HY	$1{,}2 \times 10^{6}$
HZ	6×10^{-4}

PRO - TIPS

The more negative the exponent, the smaller the value.

Consider the following statements:

I HZ is the weakest acid

II HY forms a high concentration of H_3O^+ when it ionises

III H_2X has a pH of 1.

IV HZ (aq) is more conductive than HY (aq)

Which ONE of the following statements are TRUE?

A I and II only

B I only

C II and IV only

D I, II and III only

Answer: A

Before answering the question, do an analysis of each acid, in terms of strength, by analysing the K_a values. Remember: The higher the K_a value, the stronger the acid (and vice versa)

Acid	K_a
H_2X	$2{,}8 \times 10^{-3}$
HY	$1{,}2 \times 10^{6}$
HZ	6×10^{-4}

$K_a < 1$ ∴ weak acid
Second lowest K_a value. Stronger acid than HZ but weaker than HY.

Highest K_a value; $K_a > 1$ ∴ strong acid

Lowest K_a value ∴ weakest acid
($K_a < 1$) ∴ weak acid

From the above analysis, deduce which statements are true:

I HZ is the weakest acid ✓ HZ has the lowest K_a value

II HY forms a high concentration of H_3O^+ when it ionises ✓ HY is a strong acid. Strong acids ionise completely in water to form a high concentration of H_3O^+

III H_2X has a pH of 1. ✗ H_2X is a weak acid, therefore it has a pH greater than or equal to 3, but less than 7.

IV HZ (aq) is more conductive than HY (aq) ✗ HY is a strong acid and HZ is a weak acid. Therefore HY ionises completely in water and forms a higher concentration of ions in solution ∴ more conductive.

Conclusion: Only statement I and II are true.

HYDROLYSIS (OF SALTS)

A salt is an ionic compound that consists of a positively charged ion (cation) and a negatively charged ion (anion). The salt is formed through a neutralisation reaction, where an acid reacts with a base.

Dissolving the salt in water

- When the salt is dissolved in water (with a pH = 7), it dissociates and separates into its component ions.
- In some cases, the cation **or/and** the anion reacts with water. This reaction of the ions with water is called hydrolysis. The **a**nion (-) of the salt comes from the **a**cid that reacted and the cation (+) of the salt comes from the base that reacted.

Definition: **Hydrolysis** (or salt hydrolysis): The reaction of a salt with water.

Hydrolysis (or salt hydrolysis) can alter the pH of a solution to:
acidic (if additional H_3O^+ ions form in solution)
or basic/alkaline (if additional OH^- ions form in solution).

NOTE: 'hydro' = water

Summary

Salt formed from a...	Acidic/basic/neutral salt	pH of the final solution when the salt is dissolved in water
strong acid and strong base **OR** weak acid and weak base	neutral salt	**pH = 7** (pH of the solution remains unchanged)
strong acid and weak base	acidic salt	**pH < 7** (pH of final solution is acidic)
weak acid and strong base	basic salt	**pH > 7** (pH of final solution is basic)

NOTE: To alter the pH of the solution, it is usually only one of the ions [either the anion (-) or the cation (+)] that reacts with water. These are ions from weak acids and weak bases.

Common ions that do not hydrolyse

- Anions from **strong acids** e.g., SO_4^{2-}, Cl^-, NO_3^- → These are **weak** conjugate bases of strong acids.

Anion from H_2SO_4
Anion from HCl
Anion from HNO_3

- Cations from strong bases e.g., cations of metals in group I (K^+, Li^+, Na^+) and group II (Ca^{2+}, Ba^{2+})

Cation from KOH
Cation from LiOH
Cation from NaOH
Cation from $Ca(OH)_2$
Cation from $Ba(OH)_2$

PRO - TIPS

- If the acid is a strong acid, its conjugate base is a weak base.
- If the base is a strong base, its conjugate acid is a weak acid.

Example 1: Consider the salt Na_2CO_3.

To determine whether this salt will hydrolyse or not, the ions that form in solution must be analysed to determine which acid and base reacted to form the salt and the strength of the acid and base that reacted.

Na_2CO_3 is dissolved in water and dissociates:

$$Na_2CO_3 \xrightarrow{H_2O} 2Na^+ + CO_3^{2-}$$

Analyse the ions

Cation (from the base): Na^+

Base that reacted to form the salt: NaOH (Strong base)

Conclusion: Cations from strong bases will not hydrolyse. ✗

Na_2CO_3 is a basic salt

Anion (from the acid): CO_3^{2-}

Acid that reacted to form the salt: H_2CO_3(Weak acid)

Conclusion: Anions from weak acids will hydrolyse. ✓

NOTE: Only the CO_3^{2-} ion from the salt Na_2CO_3 will react with water.

Hydrolysis reaction:

$$\underset{\text{base}}{CO_3^{2-}(aq)} + \underset{\text{acid}}{H_2O(l)} \rightleftharpoons HCO_3^-(aq) + \mathbf{OH^-}(aq)$$

Conclusion: The addition of OH^- increases the pH of the solution (pH > 7).

Example 2: Consider the salt NH_4Cl

To determine whether this salt will hydrolyse or not, the ions that form in solution must be analysed to determine which acid and base reacted to form the salt and the strength of the acid and base that reacted.

NH_4Cl is dissolved in water and dissociates:

$$NH_4Cl \xrightarrow{H_2O} NH_4^+ + Cl^-$$

Analyse the ions

Cation (from the base): NH_4^+

Base that reacted to form the salt: NH_4OH **OR** NH_3 (Weak base)

Conclusion: Cations from weak bases will hydrolyse. ✓

NH_4Cl is an acidic salt

Anion (from the acid): Cl^-

Acid that reacted to form the salt: HCl (Strong acid)

Conclusion: Anions from strong acids will not hydrolyse. ✗

Hydrolysis reaction:

NOTE: Only the NH_4^+ ion from the salt NH_4Cl will react with water.

$$\underset{\text{acid}}{NH_4^+(aq)} + \underset{\text{base}}{H_2O(l)} \rightleftharpoons NH_3(aq) + \mathbf{H_3O^+}(aq)$$

NOTE: The states of matter do not need to be included in the hydrolysis equation

Conclusion: The addition of H_3O^+ decreases the pH of the solution (pH < 7).

Worked example

Multiple choice question

1. NaCl is dissolved in water. Which ONE of the following represents how NaCl will alter the pH of the solution?

A Increases

B Decreases

C Remains the same

D Increases then decreases

PRO – TIPS

Not all salts hydrolyse; and therefore not all salts alter the pH of the solution when they are dissolved in water.

Answer: C

NaCl is a salt (ionic compound). When it dissolves in water, it will only alter the pH of the solution **if** one of the ions (anion or cation) hydrolyses i.e., reacts with the water.
NaCl forms Na^+ and Cl^- ions when it dissolves in water.
Anion (Cl^-) from the acid that reacted to form the salt: HCl (strong acid)
Cation (Na^+) from the base that reacted to form the salt: NaOH (strong base)

Remember: Anions and cations from strong acids and strong bases will not hydrolyse, therefore the pH of the solution remains the same (pH =7)

pH SCALE AND CALCULATING pH

The pH scale is a scale of numbers from 0 to 14 used to express the acidity or alkalinity of a solution.The pH values (0 - 14) indicate the concentration of the hydronium ions $[H_3O^+]$ in solution.

In a solution, $[H^+] = [H_3O^+]$ Hydrogen ions (H^+) cannot exist in isolation, therefore H^+ bond to water molecules in solution to form H_3O^+

Detailed pH scale

pH stands for "power of hydrogen" or "potential of hydrogen".

	Acid (pH < 7)							Neutral (pH = 7)	Basic (pH > 7)						
pH	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
$[H_3O^+]$	10^0	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}	10^{-13}	10^{-14}
$[H^+]$	10^0	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}	10^{-13}	10^{-14}
$[OH^-]$	10^{-14}	10^{-13}	10^{-12}	10^{-11}	10^{-10}	10^{-9}	10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	10^0

← **More acidic** **More basic** →

Conclusions from the detailed pH scale

- $[H_3O^+] = [H^+]$ in a solution.
- All solutions have H_3O^+ and OH^- ions in solution. As the $[H_3O^+]$ increases, the $[OH^-]$ decreases.
- However, acids have higher concentrations of H_3O^+ in solution and bases have higher concentrations of OH^-
- Strong acids have a higher concentration of H_3O^+ in solution than weak acids because strong acids ionise completely in water. The stronger the acid, the higher the concentration of H_3O^+ ions in solution.
- Strong bases have a higher concentration of OH^- in solution than weak bases, because strong bases dissociate completely in water.
- In a neutral substance (pH = 7), the $[H_3O^+] = [OH^-]$

Calculating pH: The auto - ionisation of water

Water is an **ampholyte**. It is able to act as an acid in some reactions, and a base in other reactions.

Water is therefore able to **self-ionise** to an extremely limited extent (autoprotolysis), where water molecules react with other water molecules.

Auto- ionisation of water: The reaction of water with itself to form H_3O^+ ions and OH^- ions.

The equilibrium reaction can be represented as:

$$H_2O\ (l) + H_2O\ (l) \rightleftharpoons H_3O^+(aq) + OH^-\ (aq)$$

base 1 **acid 2** **Conjugate acid 2** **Conjugate base 1**

The concentration of the ions namely, H_3O^+ (aq) and OH^- (aq) in solution, is extremely low.

The ionisation constant for water (K_w)

At equilibrium, the ionisation constant of water, K_w, is equal to:

$$K_w = \frac{[products]}{[reactants]}$$

NOTE: [ ] = concentration

$$K_w = \frac{[H_3O^+][OH^-]}{1.1}$$

$$\therefore K_w = [H_3O^+][OH^-]$$

Remember: Water is a pure liquid, the concentration of water is constant and taken as 1.

$$\therefore K_w = (1 \times 10^{-7})(1 \times 10^{-7})$$

$$\therefore \mathbf{K_w = 1 \times 10^{-14}} \textbf{ at 25°C or 298 K}$$

Water has a pH = 7

From the detailed pH scale, in a neutral solution:

$[H_3O^+] = [OH^-] = 1 \times 10^{-7}$

PRO - TIPS

As with all equilibrium constants (K_c, K_a, K_b and K_w) the only factor that can affect the equilibrium constant is a **change in temperature**.

On data sheet

$$K_w = [H_3O^+][OH^-] = 1 \times 10^{-14} \text{ at } 298\text{ K}$$

This formula can be used to interchange between the $[H_3O^+]$ and $[OH^-]$ in a solution

Formula to calculate the pH of a solution

	Acid (pH < 7)							Neutral (pH = 7)	Basic (pH > 7)						
pH	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
$[H_30^+]$	10^0	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}	10^{-13}	10^{-14}
$[H^+]$	10^0	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}	10^{-13}	10^{-14}
$[OH^-]$	10^{-14}	10^{-13}	10^{-12}	10^{-11}	10^{-10}	10^{-9}	10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	10^0

From the detailed pH scale it can be concluded:

$$[H_3O^+] = 10^{-pH}$$

This formula can be used to calculate the $[H_3O^+]$ in a solution, if the pH of the solution is known.

PRO - TIPS

Use the log button on the calculator to do pH calculations involving logarithms (logs).

Using the above formula and a mathematical application called logarithms, the pH formula can be derived::

$$pH = -\log[H_3O^+]$$

Formula on data sheet

pH has no units

pH is the negative log of the hydronium ion concentration.

To calculate the pH of a solution, the $[H_3O^+]$ must be known or determined.

Worked example

c

1.1 Calculate the pH of a solution with a $[H_3O^+] = 1 \times 10^{-4}$ mol.dm^{-3}.
1.2 Is the solution acidic or basic? Is it a strong or weak acid /base?
1.3 Calculate the concentration of hydroxide ions in solution.

1.1 The concentration of hydronium ions $[H_3O^+]$ in the solution is known, this can be used to determine the pH of the solution:

$pH = -\log [H_3O^+]$
$pH = -\log [1 \times 10^{-4}]$
$pH = 4$

pH has no units

1.2 The pH of the solution is less than 7, therefore it is acidic. Remember strong acids have a pH greater than or equal to 0, but less than 3.
Weak acids have a pH greater than or equal 3, but less than 7.
∴ Acidic. Weak acid.

1.3 K_w(the ionisation constant for water) at 298 K, can be used to interchange between the concentration of H_3O^+ and OH^- ions in a solution.

$[H_3O^+][OH^-] = 1 \times 10^{-14}$
$(1 \times 10^{-4})[OH^-] = 1 \times 10^{-14}$
$[OH^-] = \frac{1 \times 10^{-14}}{1 \times 10^{-4}}$
$[OH^-] = 1 \times 10^{-10}$ mol.dm^{-3}

CALCULATING THE pH OF KNOWN STRONG ACIDS AND BASES

pH of strong acids

Strong acids ionise completely in water form a high $[H_3O^+]$, therefore:

- **Monoprotic strong acids** (e.g., HCl, HNO_3) ionise completely in **ONE** step:

$$HCl\ (g) + H_2O\ (l) \rightleftharpoons H_3O^+\ (aq) + Cl^-\ (aq)$$

$n(HCl) : n(H_3O^+)$
1 mol : 1 mol

∴ For a monoprotic acid: $[H_3O^+] = [acid]$

- **Diprotic strong acids** (e.g., H_2SO_4) ionises completely in **TWO** steps:

Step 1: $H_2SO_4 + H_2O \rightarrow H_3O^+ + HSO_4^-$

Step 2: $HSO_4^- + H_2O \rightarrow H_3O^+ + SO_4^{2-}$

$n(H_2SO_4) : n(H_3O^+)$
1 mol : 2 mol

∴ For a diprotic acid: $[H_3O^+] = 2[acid]$

- **Triprotic acids** (e.g., H_3PO_4) **assuming** it ionises completely, will ionise in **THREE** steps. It can be concluded that:

∴ For a triprotic acid: $[H_3O^+] = 3[acid]$

pH of strong bases

Strong bases dissociate completely in water to form a high $[OH^-]$ in solution.

- For a base (e.g., KOH or NaOH) where for every 1 mole of base that dissociates, 1 mole of OH^- ions form in solution: $[OH^-] = [base]$
- For a base (e.g., $Ca(OH)_2$ or $Ba(OH)_2$) where for every 1 mole of base that dissociates, 2 moles of OH^- ions form in solution: $[OH^-] = 2[base]$

Worked example

A + P

1. The acid HF ionises according to the following equation:

$$HF\,(aq) + H_2O\,(l) \rightleftharpoons H_3O^+(aq) + F^-(aq)$$

When 0,10 $mol.dm^{-3}$ solution of HF is prepared, it is found that the concentration of F^- ions is 0,018 $mol.dm^{-3}$. The temperature of the solution is 25°C.

1.1 Is HF a strong or weak acid? Explain the answer using the information given above. (2)
1.2 How will the pH of water change when solid NaF is dissolved in water? Explain the answer by writing a suitable equation. (4)

0,5 dm^3 of the 0,10 $mol.dm^{-3}$ solution of HF is now added to 0,8 dm^3 of a 0,25 $mol.dm^{-3}$ solution of NaOH.

1.3 Calculate the number of moles of hydroxide ions (OH^-) in solution at the completion of this reaction. (2)
1.4 Calculate the pH of the solution at the completion of the reaction. (6)

1.1
Note the **concentrations** of the ions formed in solution. If it is a **strong** acid, the concentration of the ions in solution will almost **equal** the concentration of the acid. If it is a **weak** acid, the concentration of ions in solution will be much **lower** than the concentration of the acid.

∴ Weak acid. The concentration of F^- ion in solution is lower than the concentration of the HF solution, therefore, HF ionised incompletely (partially) in water only, and is therefore a weak acid.

1.2 NaF is an ionic compound, therefore it is a salt. When a salt is dissolved in water, it dissociates (i.e., separates into its component ions). Salts formed from either a weak acid or weak base will hydrolyse and alter the pH of the solution.

Acid and base that reacted to form NaF?

NaF consists of Na^+ and F^- ions

Anion (F^-) from acid that reacted to form salt: HF (weak acid as concluded)
Cation (Na^+) from the base that reacted to form the salt: NaOH (strong base)
∴ F^- ion (anion from a weak acid) will hydrolyse.

Hydrolysis reaction: $\underset{\text{Base}}{F^-(aq)} + \underset{\text{Acid}}{H_2O(l)} \rightleftharpoons HF\,(aq) + OH^-(aq)$

NOTE: The states of matter do not need to be included in the hydrolysis equation

∴ The **pH of the water will increase** due to the addition of OH^- in solution, increasing the concentration of OH^- in solution

1.3 A **balanced acid - base reaction** needs to be written to determine the mole ratio in which the acid (HF) and base (NaOH) react. In this reaction, a salt and water is produced.

$$\overset{\text{Acid}}{HF} + \overset{\text{Base}}{NaOH} \longrightarrow \overset{\text{salt}}{NaF} + \overset{\text{water}}{H_2O}$$

$$H^+ \quad F^- \quad Na^+ \quad OH^-$$

[redacted]

This is not necessarily a neutralisation reaction, as the concentration and volume of both the acid and base is given, it cannot be assumed that all the moles of acid will necessarily react with all the moles of base. Determine which reactant is in excess (if any), and by how many moles the reactant is in excess:

n(HF initial) = cV
n(HF initial) = (0,1)(0,5)
n(HF initial) = 0,05 mol

n(NaOH initial) = cV
n(NaOH initial) = (0,25)(0,8)
n(NaOH initial) = 0,2 mol

n(HF used up) : n(NaOH used up)
1 mol : 1 mol

∴ NaOH is in excess (HF is the limiting reagent).

n(NaOH used up) = 0,05 mol

All the initial moles of HF (0,05 mol) was used up. From the mole ratio, only 0,05 mol of NaOH will be used up.

n(NaOH in excess) = n(NaOH initial) – n(NaOH used up)
n(NaOH in excess) = 0,2 – 0,05
n(NaOH in excess) = 0,15 mol

For every 1 mol of NaOH that dissociates, 1 mol of OH^- form in solution.

∴ n(OH^-) = n(NaOH in excess) = 0,15 mol

1.4 **Remember:** To calculate the pH of final solution, the concentration of H_3O^+ ions in solution needs to be determined.

Volume of the final solution

In the final solution, the volume of acid was added to the volume of base, therefore the total volume of the final solution, is the sum of the volumes of the acid and base.

Number of moles

All the moles of HF (acid) was used up, however, there was 0,15 mol of NaOH in excess, these excess moles of NaOH can be used to determine the concentration of OH^- ions in solution, and can be used to determine the concentration of H_3O^+ ions in solution, using K_w, and thereafter the pH of the final solution.

Calculate the concentration of OH^- ions in solution (using K_w, this can be converted to the concentration of H_3O^+ ions in solution).

$c(OH^-) = \frac{n}{V}$
$c(OH^-) = \frac{(0,15)}{(0,5+0,8)}$
$c(OH^-) = 0,115\ldots \text{ mol.dm}^{-3}$

$[H_3O^+][OH^-] = 1 \times 10^{-14}$
$[H_3O^+](0,115\ldots) = 1 \times 10^{-14}$
$[H_3O^+] = \frac{1 \times 10^{-14}}{0,115\ldots}$
$[H_3O^+] = 8,666\ldots \times 10^{-14} \text{ mol.dm}^{-3}$

Use K_w to interchange between $[OH^-]$ and $[H_3O^+]$

pH = $-\log[H_3O^+]$
pH = $-\log(8,666\ldots \times 10^{-14})$
pH = 13,06

This is within the pH range (12 - 14) of a strong base, such as NaOH.

ELECTROCHEMISTRY

Revision from grade 11

REDOX reactions

A REDOX reaction is an oxidation - reduction reaction (or reduction - oxidation reaction) that involves the **transfer of electrons.**

Oxidation (in terms of electron transfer): Is a **loss** of electrons.

Reduction (in terms of electron transfer): Is a **gain** of electrons.

Did you know? **Rust** is a common example of a REDOX reaction

Remember: when a substance gains electrons, it's charge is reduced.

To remember the definition of oxidation and reduction in terms of electron transfer, the following acronym can be used:

OIL	**RIG**
Oxidation is a loss of electrons	Reduction is a gain of electrons

OR

LEO	**GER**
Loss of electrons is oxidation	Gain of electrons is reduction

In order for a susbstance to lose electrons, there must be another substance available to gain the electrons, therefore, oxidation and reduction always occur together and where there is oxidation (a loss of electrons) there is reduction (a gain of electrons). The substances involved in the electron transfer are called **oxidising agents** and **reducing agents**.

Oxidising agent: A substance that is reduced/ gains electrons
Reducing agent: A substance that is oxidised/ loses electrons

Spectator ions

A spectator ion is a ion i.e., a cation or anion that exists in the same form on both the reactant and product side of a chemical reaction.
These are ions that are not involved in the electron transfer (but are necessary for the reaction to take place).

NOTE: Some, but not all REDOX reactions have spectator ions.

Common example of a REDOX reaction: $Zn\,(s) + 2HCl\,(aq) \rightarrow ZnCl_2(aq) + H_2(g)$

Assign charges to the atoms or ions that make up the substances:

$\overset{0}{Zn}\,(s) + \overset{2(+1)\,2(-1)}{2HCl}\,(aq) \rightarrow \overset{+2\;\;2(-1)}{ZnCl_2}(aq) + \overset{0}{H_2}(g)$

NOTE: The charges are indicated in brackets.
The coefficients balance the number of atoms.

Neutral atoms and diatomic molecules are assigned a charge 0

Analyse the change in charge for each species:

Zn: 0 to +2 ∴ lost e^- ∴ oxidised/underwent oxidation
∴ reducing agent

H^+ : +1 to 0 ∴ gained e^- ∴ reduced/underwent reduction
∴ oxidising agent

Spectator ion: Cl^- (**NOTE:** its charge (-1)remains unchanged from reactants to products)

Table of standard reduction potentials: Table 4A and table 4B

The Table of Standard Reduction Potentials, namely table 4 A and table 4B, is a list of common reduction - half reactions and oxidation half - reactions. Furthermore, it is a list of oxidising agents and reducing agents, in order of strength or ability. The strengths of the oxidising agents and reducing agents can also be determined using table 4A or table 4B.

Table 4A

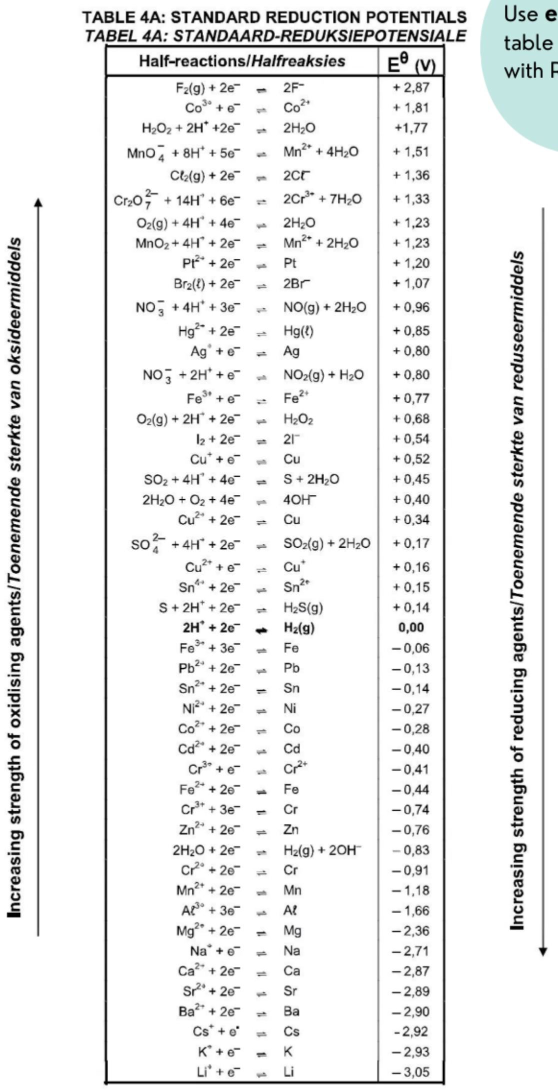


TABLE 4A: STANDARD REDUCTION POTENTIALS
TABEL 4A: STANDAARD-REDUKSIEPOTENSIALE

Half-reactions/*Halfreaksies*	**E^θ (V)**
$F_2(g) + 2e^- \rightleftharpoons 2F^-$	+ 2,87
$Co^{3+} + e^- \rightleftharpoons Co^{2+}$	+ 1,81
$H_2O_2 + 2H^+ + 2e^- \rightleftharpoons 2H_2O$	+1,77
$MnO_4^- + 8H^+ + 5e^- \rightleftharpoons Mn^{2+} + 4H_2O$	+ 1,51
$C\ell_2(g) + 2e^- \rightleftharpoons 2C\ell^-$	+ 1,36
$Cr_2O_7^{2-} + 14H^+ + 6e^- \rightleftharpoons 2Cr^{3+} + 7H_2O$	+ 1,33
$O_2(g) + 4H^+ + 4e^- \rightleftharpoons 2H_2O$	+ 1,23
$MnO_2 + 4H^+ + 2e^- \rightleftharpoons Mn^{2+} + 2H_2O$	+ 1,23
$Pt^{2+} + 2e^- \rightleftharpoons Pt$	+ 1,20
$Br_2(\ell) + 2e^- \rightleftharpoons 2Br^-$	+ 1,07
$NO_3^- + 4H^+ + 3e^- \rightleftharpoons NO(g) + 2H_2O$	+ 0,96
$Hg^{2+} + 2e^- \rightleftharpoons Hg(\ell)$	+ 0,85
$Ag^+ + e^- \rightleftharpoons Ag$	+ 0,80
$NO_3^- + 2H^+ + e^- \rightleftharpoons NO_2(g) + H_2O$	+ 0,80
$Fe^{3+} + e^- \rightleftharpoons Fe^{2+}$	+ 0,77
$O_2(g) + 2H^+ + 2e^- \rightleftharpoons H_2O_2$	+ 0,68
$I_2 + 2e^- \rightleftharpoons 2I^-$	+ 0,54
$Cu^+ + e^- \rightleftharpoons Cu$	+ 0,52
$SO_2 + 4H^+ + 4e^- \rightleftharpoons S + 2H_2O$	+ 0,45
$2H_2O + O_2 + 4e^- \rightleftharpoons 4OH^-$	+ 0,40
$Cu^{2+} + 2e^- \rightleftharpoons Cu$	+ 0,34
$SO_4^{2-} + 4H^+ + 2e^- \rightleftharpoons SO_2(g) + 2H_2O$	+ 0,17
$Cu^{2+} + e^- \rightleftharpoons Cu^+$	+ 0,16
$Sn^{4+} + 2e^- \rightleftharpoons Sn^{2+}$	+ 0,15
$S + 2H^+ + 2e^- \rightleftharpoons H_2S(g)$	+ 0,14
$2H^+ + 2e^- \rightleftharpoons H_2(g)$	**0,00**
$Fe^{3+} + 3e^- \rightleftharpoons Fe$	− 0,06
$Pb^{2+} + 2e^- \rightleftharpoons Pb$	− 0,13
$Sn^{2+} + 2e^- \rightleftharpoons Sn$	− 0,14
$Ni^{2+} + 2e^- \rightleftharpoons Ni$	− 0,27
$Co^{2+} + 2e^- \rightleftharpoons Co$	− 0,28
$Cd^{2+} + 2e^- \rightleftharpoons Cd$	− 0,40
$Cr^{3+} + e^- \rightleftharpoons Cr^{2+}$	− 0,41
$Fe^{2+} + 2e^- \rightleftharpoons Fe$	− 0,44
$Cr^{3+} + 3e^- \rightleftharpoons Cr$	− 0,74
$Zn^{2+} + 2e^- \rightleftharpoons Zn$	− 0,76
$2H_2O + 2e^- \rightleftharpoons H_2(g) + 2OH^-$	− 0,83
$Cr^{2+} + 2e^- \rightleftharpoons Cr$	− 0,91
$Mn^{2+} + 2e^- \rightleftharpoons Mn$	− 1,18
$A\ell^{3+} + 3e^- \rightleftharpoons A\ell$	− 1,66
$Mg^{2+} + 2e^- \rightleftharpoons Mg$	− 2,36
$Na^+ + e^- \rightleftharpoons Na$	− 2,71
$Ca^{2+} + 2e^- \rightleftharpoons Ca$	− 2,87
$Sr^{2+} + 2e^- \rightleftharpoons Sr$	− 2,89
$Ba^{2+} + 2e^- \rightleftharpoons Ba$	− 2,90
$Cs^+ + e^- \rightleftharpoons Cs$	- 2,92
$K^+ + e^- \rightleftharpoons K$	− 2,93
$Li^+ + e^- \rightleftharpoons Li$	− 3,05

Oxidising agents **Reducing agents**

PRO - TIPS

Use **either** table 4A or table 4B when working with REDOX reactions.

Table 4B

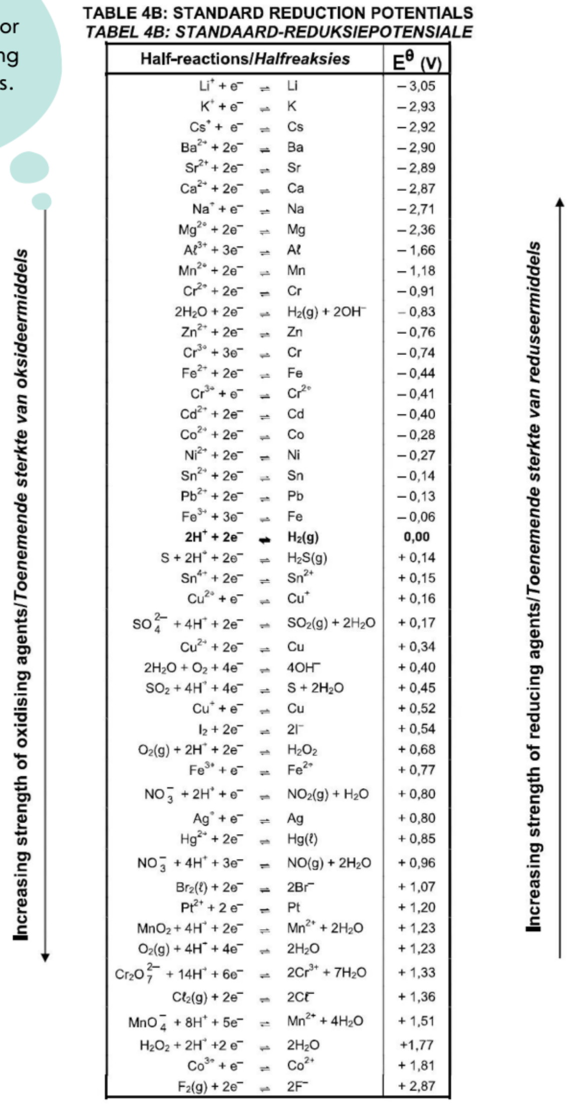


TABLE 4B: STANDARD REDUCTION POTENTIALS
TABEL 4B: STANDAARD-REDUKSIEPOTENSIALE

Half-reactions/*Halfreaksies*	**E^θ (V)**
$Li^+ + e^- \rightleftharpoons Li$	− 3,05
$K^+ + e^- \rightleftharpoons K$	− 2,93
$Cs^+ + e^- \rightleftharpoons Cs$	− 2,92
$Ba^{2+} + 2e^- \rightleftharpoons Ba$	− 2,90
$Sr^{2+} + 2e^- \rightleftharpoons Sr$	− 2,89
$Ca^{2+} + 2e^- \rightleftharpoons Ca$	− 2,87
$Na^+ + e^- \rightleftharpoons Na$	− 2,71
$Mg^{2+} + 2e^- \rightleftharpoons Mg$	− 2,36
$A\ell^{3+} + 3e^- \rightleftharpoons A\ell$	− 1,66
$Mn^{2+} + 2e^- \rightleftharpoons Mn$	− 1,18
$Cr^{2+} + 2e^- \rightleftharpoons Cr$	− 0,91
$2H_2O + 2e^- \rightleftharpoons H_2(g) + 2OH^-$	− 0,83
$Zn^{2+} + 2e^- \rightleftharpoons Zn$	− 0,76
$Cr^{3+} + 3e^- \rightleftharpoons Cr$	− 0,74
$Fe^{2+} + 2e^- \rightleftharpoons Fe$	− 0,44
$Cr^{3+} + e^- \rightleftharpoons Cr^{2+}$	− 0,41
$Cd^{2+} + 2e^- \rightleftharpoons Cd$	− 0,40
$Co^{2+} + 2e^- \rightleftharpoons Co$	− 0,28
$Ni^{2+} + 2e^- \rightleftharpoons Ni$	− 0,27
$Sn^{2+} + 2e^- \rightleftharpoons Sn$	− 0,14
$Pb^{2+} + 2e^- \rightleftharpoons Pb$	− 0,13
$Fe^{3+} + 3e^- \rightleftharpoons Fe$	− 0,06
$2H^+ + 2e^- \rightleftharpoons H_2(g)$	**0,00**
$S + 2H^+ + 2e^- \rightleftharpoons H_2S(g)$	+ 0,14
$Sn^{4+} + 2e^- \rightleftharpoons Sn^{2+}$	+ 0,15
$Cu^{2+} + e^- \rightleftharpoons Cu^+$	+ 0,16
$SO_4^{2-} + 4H^+ + 2e^- \rightleftharpoons SO_2(g) + 2H_2O$	+ 0,17
$Cu^{2+} + 2e^- \rightleftharpoons Cu$	+ 0,34
$2H_2O + O_2 + 4e^- \rightleftharpoons 4OH^-$	+ 0,40
$SO_2 + 4H^+ + 4e^- \rightleftharpoons S + 2H_2O$	+ 0,45
$Cu^+ + e^- \rightleftharpoons Cu$	+ 0,52
$I_2 + 2e^- \rightleftharpoons 2I^-$	+ 0,54
$O_2(g) + 2H^+ + 2e^- \rightleftharpoons H_2O_2$	+ 0,68
$Fe^{3+} + e^- \rightleftharpoons Fe^{2+}$	+ 0,77
$NO_3^- + 2H^+ + e^- \rightleftharpoons NO_2(g) + H_2O$	+ 0,80
$Ag^+ + e^- \rightleftharpoons Ag$	+ 0,80
$Hg^{2+} + 2e^- \rightleftharpoons Hg(\ell)$	+ 0,85
$NO_3^- + 4H^+ + 3e^- \rightleftharpoons NO(g) + 2H_2O$	+ 0,96
$Br_2(\ell) + 2e^- \rightleftharpoons 2Br^-$	+ 1,07
$Pt^{2+} + 2e^- \rightleftharpoons Pt$	+ 1,20
$MnO_2 + 4H^+ + 2e^- \rightleftharpoons Mn^{2+} + 2H_2O$	+ 1,23
$O_2(g) + 4H^+ + 4e^- \rightleftharpoons 2H_2O$	+ 1,23
$Cr_2O_7^{2-} + 14H^+ + 6e^- \rightleftharpoons 2Cr^{3+} + 7H_2O$	+ 1,33
$C\ell_2(g) + 2e^- \rightleftharpoons 2C\ell^-$	+ 1,36
$MnO_4^- + 8H^+ + 5e^- \rightleftharpoons Mn^{2+} + 4H_2O$	+ 1,51
$H_2O_2 + 2H^+ + 2e^- \rightleftharpoons 2H_2O$	+1,77
$Co^{3+} + e^- \rightleftharpoons Co^{2+}$	+ 1,81
$F_2(g) + 2e^- \rightleftharpoons 2F^-$	+ 2,87

Oxidising agents **Reducing agents**

Table 4A **VS** **Table 4B**

Similarities

- Table **4** and **B** provides a list of possible half reactions.
- All half reactions are written as reversible reactions.
- All half reactions from **left to right are reduction half – reactions** (gain of electrons) – therefore all substances on the **left are oxidising agents**
- All half reactions read from **right to left are oxidation half - reactions** (loss of electrons) - therefore all substances on the **right are reducing agents**

Differences

Table 4A **VS** **Table 4B**

Oxidising agents (Substances on the left of table 4A and table 4B)

NOTE: F_2 is the **strongest oxidising agent**, and is most likely to gain electrons due to it having the highest electronegativity and Li^+ is the **weakest oxidising agent**, as it has a very low electronegativity.

In table 4**A** the strength of the oxidising agents increase moving **UP, left.** **The higher to the left of table 4A, the stronger the oxidising agent.**

VS

In table 4**B** the strength of the oxidising agents increase moving **DOWN, left.** **The lower to the left of table 4B, the stronger the oxidising agent.**

Reducing agents (Substances on the right of table 4A and table 4B)

NOTE: Li is the **strongest reducing agent**, and is most likely to lose electrons due to it having a very low electronegativity and F^- is the **weakest reducing agent**, and is not likely to lose electrons.

In table 4**A** the strength of the reducing agents increase moving **DOWN, right.** **The lower to the right of table 4A, the stronger the reducing agent.**

In table 4**B** the strength of the reducing agents increase moving **UP, right.** **The higher to the right of table 4B, the stronger the reducing agent.**

Using table 4A and table 4B to determine if a REDOX reaction is a spontaneous or non - spontaneous REDOX reaction

Spontaneous REDOX reactions

- A spontaneous reaction is a reaction that favours the formation of products at the conditions under which the reaction is occurring.
- **For a spontaneous REDOX reaction to take place:** A **stronger** reducing agent must react with a **stronger** oxidising agent.
- All spontaneous REDOX reactions are **exothermic reactions** ($\triangle H < 0$)

Remember: an exothermic reaction increases the temperature.

Non - spontaneous REDOX reactions

- A non - spontaneous reaction is a reaction that requires additional energy for the reaction to proceed.
- In a non - spontaneous REDOX reaction: A **weaker** reducing agent reacts with a **weaker** oxidising agent.
- All non - spontaneous REDOX reactions are **endothermic reactions** ($\triangle H > 0$)

Remember: an endothermic reaction decreases the temperature.

NOTE: By looking at the strength of the oxidising and reducing agents on table 4A or table 4B, it can be determined if a REDOX reaction is spontaneous or non - spontaneous. This will be covered later in detail. .

Oxidation numbers

Oxidation numbers were covered in grade 11.

An oxidation number is a number assigned to each element in a compound in order to keep track of the movement of electrons in a reaction.

Why are oxidation numbers used?

- To help chemists balance redox reactions
- To indicate the loss or gain of electrons

In a chemical reaction, oxidation and reduction can be defined in terms of oxidation numbers:
Oxidation is an increase in oxidation number.
Reduction is a decrease in oxidation number.

Rules for assigning oxidation numbers

1. The oxidation number of neutral, unbonded atoms is 0.
   E.g., Ca **O.N = 0**

2. For diatomic molecules, H_2 , O_2, N_2,Cl_2, F_2 , Br_2 , I_2 , the oxidation number is 0.

3. The oxidation number of fluorine (**F**) is always – 1.

4. In monoatomic ions the oxidation number is the same as the charge on the ion e.g., Mg^{2+} O.N = +2.

5. The **sum** of the oxidation numbers in a neutral compound is 0. E.g., MgO **sum** of ON = 0

6. The **sum** of the oxidation numbers in a polyatomic ion is equal to the overall charge of the ion.E.g., SO_4^{2-} **sum** of ON = -2

7. The oxidation number of hydrogen is **usually** +1, when it bonds to a non - metal.
   E.g., HCl O.N of H = +1
   Exception: When hydrogen is bonded to a metal (to form a metal hydride), then its oxidation number
   is -1 (as it is the more electronegative element in the compound)
   E.g., LiH, NaH O.N of H = -1

8. The oxidation number of oxygen is **usually** -2.
   Exception: in peroxides(e.g. H_2O_2, Na_2O_2), in which the oxidation number of oxygen is **-1**.
   Additionally, in all bonds with fluorine (F), which is more electronegative than oxygen, e.g., in OF_2 , the oxidation number of O in OF_2 = +2

Example 1: Determine the oxidation number of S in H_2SO_4

H_2SO_4 is a neutral compound, therefore the **sum of the oxidation numbers must equal 0.**

$\overset{2(+1)}{H_2}\overset{x}{S}\overset{4(-2)}{O_4}$ ⟵ O.N assigned to H: +1
Note: there 2 H atoms
O.N assigned to O: -2
Note: there are 4 O atoms

Tip: Call the unknown oxidation number **x**

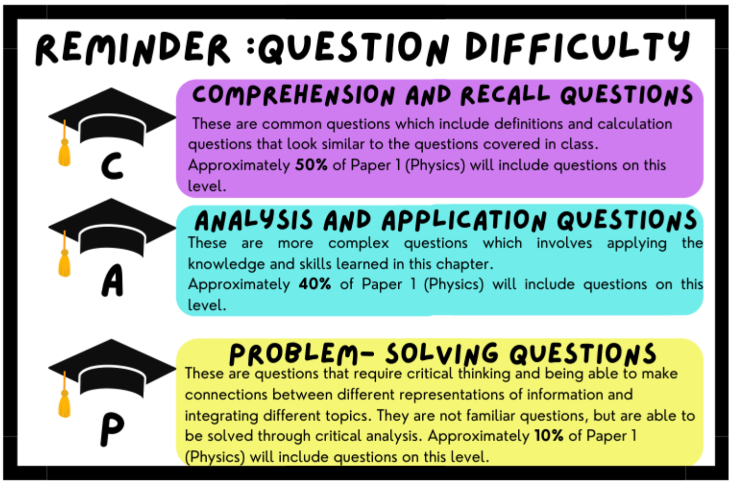
$2(+1) + x + 4(-2) = 0$
$2 + x - 8 = 0$
$x = 9 - 2$
$x = +6$
O.N of S = +6

Example 2: Determine the oxidation of Cr in $Cr_2O_7^{2-}$

$Cr_2O_7^{2-}$ is a polyatomic ion, therefore the **sum of the oxidation numbers must equal the charge -2.**

$\overset{2x}{Cr_2}\overset{7(-2)}{O_7^{2-}}$ ⟵ O.N assigned to O: -2
Note: there are 7O atoms
O.N of Cr: **2x (unknown and 2 atoms of Cr)**

$2x + 7(-2) = -2$
$2x - 14 = -2$
$2x = -2 + 14$
$2x = 12$
$x = +6$
O.N of Cr = +6



REMINDER :QUESTION DIFFICULTY

COMPREHENSION AND RECALL QUESTIONS

These are common questions which include definitions and calculation questions that look similar to the questions covered in class. Approximately **50%** of Paper 1 (Physics) will include questions on this level.

ANALYSIS AND APPLICATION QUESTIONS

These are more complex questions which involves applying the knowledge and skills learned in this chapter. Approximately **40%** of Paper 1 (Physics) will include questions on this level.

PROBLEM- SOLVING QUESTIONS

These are questions that require critical thinking and being able to make connections between different representations of information and integrating different topics. They are not familiar questions, but are able to be solved through critical analysis. Approximately **10%** of Paper 1 (Physics) will include questions on this level.

ELECTROCHEMICAL CELLS: GALVANIC CELL

There are TWO types of electrochemical cells:

1. Galvanic cell (also called a voltaic cell).
2. Electrolytic cells

The type of chemical reaction taking place in both of these electrochemical cells is a REDOX reaction.

Galvanic cell

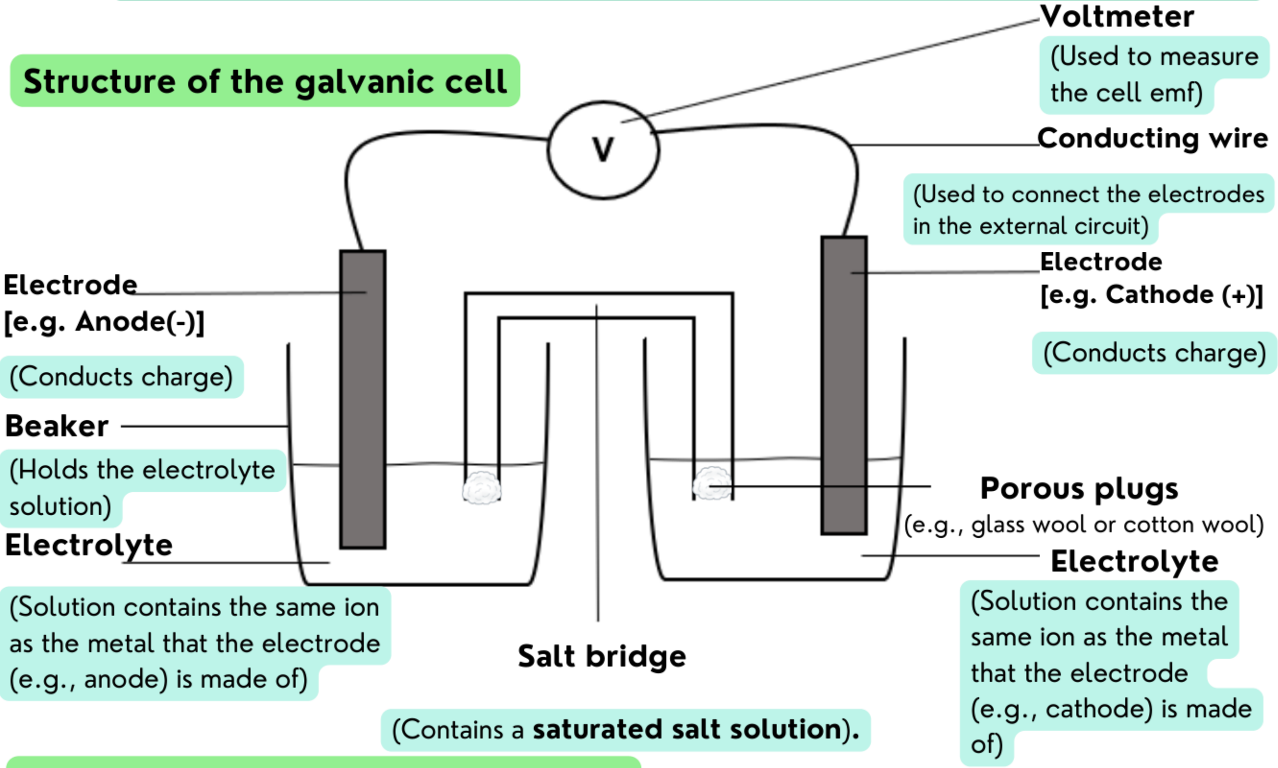
Through a spontaneous, self - sustaining REDOX reaction, chemical energy can be converted into electrical energy.

Definition: Galvanic cell: A cell in in which chemical energy is converted into electrical energy.

NOTE: A galvanic cell is battery. Batteries operate by converting chemical energy into electrical energy.

A spontaneous, self - sustaining exothermic REDOX reaction takes place in a galvanic cell.

Structure of the galvanic cell



Notes on the structure of a galvanic cell

A galvanic cell consists of **two electrodes** which are placed in separate electrolytes (electrolytic solutions), in two separate beakers, forming two **half- cells.**

Electrodes

The electrodes must be made of a **solid** that **can conduct electricity** and therefore the electrodes are usually made of a **conducting metals**. However, if one (or both) of the half-cells is a gas [e.g. chlorine gas (Cl_2) or hydrogen gas (H_2)] the electrode used is platinum (Pt) **or** in some cases, graphite (carbon) (C)

Reasons why platinum (Pt) is used:

1. Platinum is a good conductor of electricity (it is a metal)
2. Platinum is inert (unreactive)
3. Platinum **adsorbs** the gas onto its surface.

NOTE: 'adsorbs' is not be confused with 'absorbs'.
Adsorbs: To hold (molecules of a gas or liquid) as a layer on the outside surface

NOTE: If the half – cell is a **liquid**, graphite (C) can be used as the solid electrode.

Anode and cathode (electrodes)

Anode

Definition: **Anode**: Electrode where oxidation takes place. The anode is the **negative electrode** (**-**) in a galvanic cell. The anode **decreases** in mass.

PRO - TIPS

AN OX: Oxidation takes place at the anode.

RED CAT: Reduction takes place at the cathode.

Cathode

Definition: **Cathode**: Electrode where reduction takes place. The cathode is the **positive electrode** (**+**) in a galvanic cell. The cathode **increases** in mass.

NOTE: The electrodes are connected to each other in an external circuit consisting of conducting wires and a voltmeter to measure the cell emf (potential difference or voltage).

Electrolytes

- Each half cell contains an electrolyte solution.

Definition: Electrolyte: A substance of which the aqueous solution contains ions **OR** a substance that dissolves in water to give a solution that conducts electricity.

- The electrolyte solution must contain the **ion** of the metal electrode which is placed in the electrolyte solution. e.g., if the electrode is a zinc (Zn) electrode, the electrolyte solution in which the zinc electrode is placed, must contain zinc ions (Zn^{2+}), for example, a zinc nitrate solution can be used.

NOTE: Compounds containing nitrate ions are usually soluble.

Salt bridge

- A salt bridge is an inverted U- shaped tube (usually made of glass) that is filled with a suitable electrolyte(i.e., a saturated salt solution or concentrated salt solution), to allow for the movement of ions through the two half cells.
- The aqueous salt solution is kept in the U shaped tube by porous plugs in each end, such as glass wool or cotton wool, through which the ions in the salt bridge can move
- The electrolyte, which is placed in the salt bridge must a **concentrated** or **saturated** salt solution that contains ions that are weaker oxidising agents and reducing agents. Examples of saturated salt solutions that can be used include: saturated KNO_3 (aq) or $NaNO_3$(aq) or KCl (aq) or NaCl (aq).
- KNO_3 or $NaNO_3$ is usually the best option because it contains ions that are soluble in water.

Functions of the salt bridge

1. Completes the circuit.
2. Maintains electrical neutrality (allows movement of ions between the electrolytes, to ensure electrical neutrality i.e. it acts as an ion exchanger).
3. Separates the electrolytes in the two half - cells so that they do not mix.

How does the galvanic cell operate?

Flow of electrons

Electrons flow from the negative anode, through the external circuit to the positive cathode.

Remember: AN OX (at the anode oxidation takes place)
RED CAT (at the cathode reduction takes place)

Flow of ions

To maintain electrical neutrality in the half - cells, therefore there is a flow of ions from the salt bridge to the anode and cathode half cells:

- **Anions** (negative ions) from the salt bridge move towards the **anode**.
- **Cations** (positive ions) from the salt bridge move towards the **cathode**.

The reasoning behind this will be explained later in this chapter.

Standard conditions under which the galvanic cell operates

Galvanic cell with solid electrodes

Two standard conditions under which the galvanic cell operates:

- The concentration of all solutions is 1 mol.dm^{-3}
- The temperature is 25°C or 298 K.

Galvanic cell with at least one gas electrode

Four standard conditions under which the galvanic cell operates:

- The pressure of all gases is 1 atmosphere (1 atm) **OR** 101, 3 kPa
- The concentration of all solutions is 1 mol.dm^{-3}
- The temperature is 25°C (298 K)
- Platinum is the electrode used when the half – cell is a gas.

Example of a galvanic cell: Cu - Zn galvanic cell operating at standard conditions

Anode and cathode

In a galvanic cell, a spontaneous, exothermic **REDOX** reaction takes place.
In order for a spontaneous exothermic reaction to take place, a stronger oxidising agent must react with a stronger reducing agent.

Using table 4A and table 4B to determine whether Cu or Zn is a stronger reducing agent

Table 4A

Zn is a stronger reducing agent than Cu, as Zn is lower down to the right on table 4A.

Table 4B

Zn is a stronger reducing agent than Cu, as Zn is higher up, to the right on table 4B.

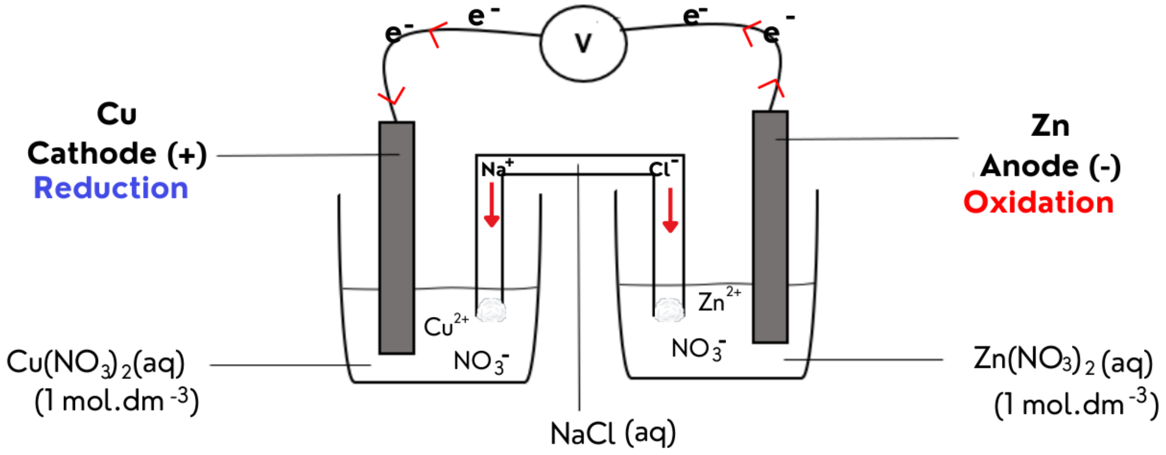
Conclusion:

Zn (zinc) is the anode electrode. → Zn is the reducing agent
Cu (copper) is the cathode electrode. → Cu^{2+} is the oxidising agent

Suitable electrolytes for the half - cells

Zn half - cell: $Zn(NO_3)_2$
Cu half - cell: $Cu(NO_3)_2$

Structure of the Cu - Zn galvanic cell



Copper half -cell [cathode(+)]	**Zinc half cell [anode(-)]**
• Cu^{2+} ions (oxidising agent)undergo reduction • Electrode increases in mass	• Zn (reducing agent) undergoes oxidation • Electrode decreases in mass

Reduction half reaction: $Cu^{2+} + 2e^- \longrightarrow Cu$

(from table 4A or table 4B)

Oxidation half reaction: $Zn \longrightarrow Zn^{2+} + 2e^-$

(from table 4A or table 4B)

Balanced net reaction: $\mathbf{Zn + Cu^{2+} \longrightarrow Zn^{2+} + Cu}$

PRO - TIPS

When writing the overall, balanced net reaction, the number of electrons lost must equal the number of electrons gained. A half reaction/s can be multiplied throughout by a factor to ensure that the number of electrons lost equals the number of electrons gained.

NOTE:

- A stronger reducing agent must react with a stronger oxidising agent in a galvanic cell.
- When writing half reactions, only **a single arrow** must be used, as the substances are only either undergoing oxidation **OR** reduction.
- No electrons are shown in the balanced net reaction, as the number of electrons lost must equal the number of electrons gained (i.e., it "cancels out")

Process

- When the Zn electrode undergoes oxidation, Zn^{2+} ions are added to the solution, increasing the concentration of Zn^{2+} (cations) in solution. To maintain electrical neutrality, Cl^- ions (anions) from the salt bridge are expelled into solution.
- The mass of the Zn electrode (anode) **decreases**.
- The Cu^{2+} ions in solution undergo reduction, forming Cu (s)which is deposited onto the Cu electrode.

  The Cu electrode (cathode) increases in mass.
- The concentration of Cu^{2+} ions in solution decreases. To maintain electrical neutrality, Na^+ (cations) from the salt bridge are expelled into the Cu half - cell.

Cell notation

The cell notation is a short- hand way of representing the reactions that occur in an electrochemical cell.

- The electrodes are written outside of the cell notation.
- A single vertical line (|) separates substances that are in different phases.
- A comma (,) separates substances that are in the same phase.
- The salt bridge is represented by two vertical lines (||)

The cell notation for a standard electrochemical cell with solid electrodes can be represented as:

Reducing agent | Oxidised species || Oxidising agent | Reduced species

Substance that loses electrons	Substance produced after the reducing agent loses electrons	Salt bridge	Substance that gains electrons	Substance produced after the oxidising agent gains electrons
Anode				**Cathode**

Example: Cell notation for the Cu - Zn galvanic cell:

$$Zn \mid Zn^{2+} \parallel Cu^{2+} \mid Cu$$

Cell notation with states of matter and standard conditions (if requested):

$$Zn\ (s) \mid Zn^{2+}(aq,\ 1\ mol.dm^{-3}) \parallel Cu^{2+}(aq,\ 1\ mol.dm^{-3}) \mid Cu\ (s) \text{ at } 25°C$$

Worked example

C + A

Write down the cell notation for an Mn and Cl_2 (g) galvanic cell

Using table 4A or table 4B, the following can be concluded:

- Mn is a stronger reducing agent than Cl^-
- Cl_2 is a stronger oxidising agent than Mn^{2+}.

For a spontaneous exothermic REDOX reaction to take place:

A stronger reducing agent must react with a stronger oxidising agent.

∴ Mn is the reducing agent and will undergo oxidation.

∴ Cl_2 is the oxidising agent and will undergo reduction.

Reduction half reaction: $Cl_2(g) + 2e^- \rightarrow 2Cl^-$
(from table 4A or table 4B)

Oxidation half reaction: $Mn \rightarrow Mn^{2+} + 2e^-$
(from table 4A or table 4B)

Cell notation:

$$Mn \mid Mn^{2+} \parallel Cl_2 \mid Cl^- \mid Pt$$

PRO - TIPS

Write out the oxidation half reaction and the reductional half reaction to make it easier to write the cell notation.
No coefficients are included in the cell notation.

NOTE:

- One of the electrodes is a gas [$Cl_2(g)$]. Therefore a platinum solid (Pt) electrode is used, this must be indicated at the end of the cell notation with the gaseous half - cell.

Cell emf ($E^\ominus_{cell}$)

- The **standard reduction potential**, measured in volts, is present on table 4A and table 4B as $E^\ominus$(V).
- The standard reduction potential gives an indication of how likely a substance is able to be reduced or oxidised, and can interpreted as follows:

A **large positive standard reduction potential** indicates that the substance is more likely to be reduced (it is a stronger oxidising agent)

A **large negative standard reduction potential** indicates that a substance is more likely to be oxidised (it is a stronger reducing agent).

A REDOX reaction has TWO half- reactions taking place simultaneously. The two half cells (electrodes) must be connected and the potential difference across the two half cells, known as the cell emf or cell potential ($E^\ominus_{cell}$) at standard conditions, is a combination of the two standard reduction potentials and is measured using a voltmeter or it can be calculated using the one of the following formulae:

$$E^\theta_{cell} = E^\theta_{cathode} - E^\theta_{anode}$$

OR

$$E^\theta_{cell} = E^\theta_{reduction} - E^\theta_{oxidation}$$

OR

$$E^\theta_{cell} = E^\theta_{oxidising agent} - E^\theta_{reducing agent}$$

What do these variables mean and what are the SI units?

$E^\ominus_{cell}$ = cell emf in volts (V)

$E^\ominus_{cathode}$ **OR**
$E^\ominus_{reduction}$ **OR**
$E^\ominus_{oxidising\ agent}$

At the **cathode reduction** takes place and the substance undergoing reduction is the **oxidising agent**

=emf (standard reduction potential) in volts (V)

E_{anode} **OR**
$E_{oxidation}$ **OR**
$E_{reducing\ agent}$

At the **anode oxidation** takes place and the substance undergoing oxidation is the **reducing agent**

=emf (standard reduction potential) in volts (V)

NOTE: E represents emf (E) at **standard conditions** measured in volts (V)
When the REDOX reaction is a spontaneous exothermic reaction, $E^\ominus_{cell}$ (cell emf) is **positive**.For a galvanic cell, the cell emf is always positive.

Example: Calculate the initial cell emf for the Cu - Zn galvanic cell

$$E^\ominus_{cell} = E^\ominus_{cathode} - E^\ominus_{anode}$$
$$E^\ominus_{cell} = (0{,}34) - (-0{,}76)$$
$$E^\ominus_{cell} = +1{,}10\ \text{V}$$

A positive cell emf indicates that a spontaneous exothermic reaction is taking place.

Cell emf and chemical equilibrium

- All galvanic cells can reach equilibrium.
- When a galvanic cell reaches equilibrium, the rate of oxidation equals the rate of reduction OR the rate of the forward reaction equals the rate of the reverse reaction. The cell (battery) goes "flat" and the cell emf is **zero** (0V).

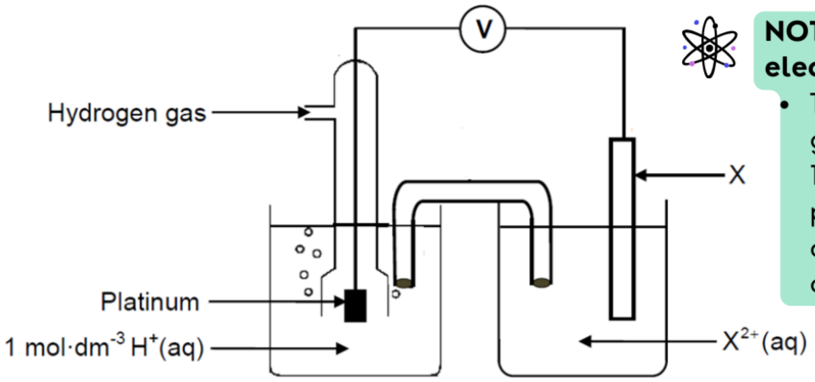
Effects of changing the standard conditions - chemical equiibrium

- Favouring the **forward reaction increases the cell emf**. The cell emf is greater than that calculated under standard conditions.
- Favouring the **reverse reaction decreases the cell emf**. The cell emf is lower than that calculated under standard conditions.

GALVANIC CELLS: STANDARD HYDROGEN ELECTRODE

- The standard hydrogen half cell operating at standard conditions was assigned a half cell potential (standard reduction potential) of **0,00V.**
- **The standard reduction potential ($E^{\ominus}$ value)** of **all** other half cells in measured relative to the standard hydrogen half cell.

Figure 1 below represents a hydrogen half - cell connected to another half - cell **X.**



NOTE: In the standard hydrogen electrode:

- The hydrogen is pumped through a glass tube at a standard pressure of 1 atm and is bubbled over a platinum electrode which is in contact with a acid solution with a concentration of 1 mol.dm^{-3}

Figure 1

Standard conditions under which the standard hydrogen electrode operates:

✓ The pressure of H_2 gas is 1 atmosphere (1 atm) **OR** 101, 3 kPa.
✓ The concentration of the **strong acid** solution (containing H^+ ions) is 1 mol.dm^{-3}
✓ The temperature is 25°C (298 K).
✓ Solid platinum is the electrode used.

Conclusions regarding the voltmeter reading when a half - cell is connected to a standard hydrogen half - cell

A **positive voltmeter reading** indicates that the **other electrode is the cathode** (+)

A **negative voltmeter reading** indicates that the **other electrode is the anode** (-)

Worked example

1. A galvanic cell operates according to the following UNBALANCED reaction:

$$Ag^{+}(aq) + Zn(s) \longrightarrow Ag(s) + Zn^{2+}(aq)$$

1.1 Write down the NAME of the substance that the ANODE is made of. Give a reason for the answer by referring to the oxidation numbers. (2)

1.2 Write down the NAME of the solid metal that the CATHODE is made of. (1)

The Ag electrode is now replaced with a $Mn|Mn^{2+}$ electrode.

1.3 Write down the:
  - 1.3.1 Oxidation half reaction (2)
  - 1.3.2 Reduction half reaction (2)
  - 1.3.3 Balanced net reaction (2)

1.4 Write down the cell notation for the cell. (4)

1.5 Which galvanic cell (Ag - Zn or Zn - Mn) produced a greater cell emf? Prove the answer with a calculation. (2)

1.6 After a certain time period the Zn - Mn galvanic cell has a cell emf of 0V. Explain why this occurs. (5)

1.1 Assign oxidation numbers to determine which substance was oxidised and which substance was reduced.

$$\overset{+1}{Ag^{+}}(aq) + \overset{0}{Zn}(s) \longrightarrow \overset{0}{Ag}(s) + \overset{+2}{Zn^{2+}}(aq)$$

The oxidation number of Ag^{+} decreased from +1 to 0. Ag^{+} was reduced/ underwent reduction ∴oxidising agent

The oxidation number of Zn increased from 0 to +2. Zn was oxidised/ underwent oxidation ∴reducing agent

Zinc. The oxidation number of Zn increased from 0 to +2, therefore Zn underwent oxidation and is therefore the anode.

1.2 Ag^{+}(in solution) were reduced. The electrode is a solid, therefore it is **silver**.

1.3 **Analysis:**

Compare the strength of Mn and Zn as a reducing agent using table 4A or table 4B:

Table 4A	**Table 4B**
Mn is a stronger reducing agent than Zn, as Mn is lower down to the right on table 4A.	Mn is a stronger reducing agent than Zn , as Mn is higher up, to the right on table 4B.

Conclusion:

Reducing agent: Mn → Undergoes oxidation

Oxidising agent: Zn^{2+} → Undergoes reduction

1.3.1 Oxidation half reaction: $Mn \longrightarrow Mn^{2+} + 2e^-$

Remember: Oxidation is a loss of electrons. The reverse reaction on table 4A and table 4B is the oxidation half reaction.

1.3.2 Reduction half reaction: $Zn^{2+} + 2e^- \longrightarrow Zn$

1.3.3 Balanced net reaction: $Mn + Zn^{2+} \longrightarrow Mn^{2+} + Zn$

Remember: When writing the overall balanced net reaction, make sure of the following:
The number of electrons lost equals the number of electrons gained.
The net reaction is balanced.

1.4 **Remember the order of the cell notation.**

Reducing agent	|	**Oxidised species**	||	**Oxidising agent**	|	**Reduced species**
Substance that loses electrons		Substance produced after the reducing agent loses electrons	Salt bridge	Substance that gains electrons		Substance produced after the oxidising agent gains electrons

∴ $Mn \mid Mn^{2+} \parallel Zn^{2+} \mid Zn$

1.5 The cell emf for each galvanic cell needs to be calculated and compared:

Cell emf Ag - Zn galvanic cell

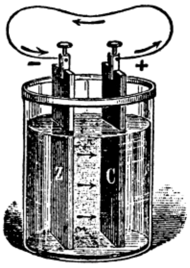
$$E^\theta_{cell} = E^\theta_{cathode} - E^\theta_{anode}$$
$$E^\theta_{cell} = (+0{,}80) - (-0{,}76)$$
$$E^\theta_{cell} = 1{,}56\ V$$

Cell emf Zn - Mn galvanic cell

$$E^\theta_{cell} = E^\theta_{cathode} - E^\theta_{anode}$$
$$E^\theta_{cell} = (-0{,}76) - (-1{,}18)$$
$$E^\theta_{cell} = 0{,}42\ V$$

∴ The Ag - Zn galvanic cell produces a greater cell emf.

1.6
- All galvanic cells can reach equilibrium.
- When a galvanic cell reaches equilibrium, the rate of oxidation equals the rate of reduction OR the rate of the forward reaction equals the rate of the reverse reaction. The cell (battery) goes "flat" and the cell emf is **zero** (0V).



ELECTROLYTIC CELLS

- An electrolytic cell is different from a galvanic cell in that in an electrolytic cell, **electrical energy** is converted into **chemical energy**.
- An electrolytic cell therefore requires additional energy from a **DC (direct current) power source**, such as a battery because the REDOX reaction that takes place in a electrolytic cell is a **non - spontaneous endothermic reaction**, where a weaker reducing agent reacts with a weaker oxidising agent.

Definition: Electrolytic cell: a cell in which electrical energy is converted into chemical energy

NOTE: In an electrolytic cell:

- The **anode** is the **positive electrode** (+)
- The **cathode** is the **negative electrode** (-)
- The anode is connected to the positive terminal of the battery and the cathode is connected to the negative terminal of the battery.

Opposite of a galvanic cell

Still applies to an electrolytic cell:

AN OX (at the anode oxidation takes place)

RED CAT (at the cathode reduction takes place)

PRO - TIPS

The cell emf in an electrolytic cell is **negative** because a non - spontaneous REDOX reaction takes place.

Electrolytic processes covered in this chapter:

- The decomposition of copper(II) chloride
- Electroplating, e.g. the electroplating of an iron spoon with silver/nickel
- Refining of metals, e.g. copper
- The electrolysis of a concentrated solution of sodium chloride

The decomposition of copper (II) chloride (electrolysis)

- A solution of copper (II) chloride ($CuCl_2$) of concentration 1 $mol.dm^{-3}$ is prepared.
- The solution is **initially** blue in colour due to the presence of Cu^{2+} ions in solution.
- Two conductive graphite electrodes are used.

Figure 2 below represents the structure of electrolytic cell used for the decomposition of $CuCl_2$ (aq)

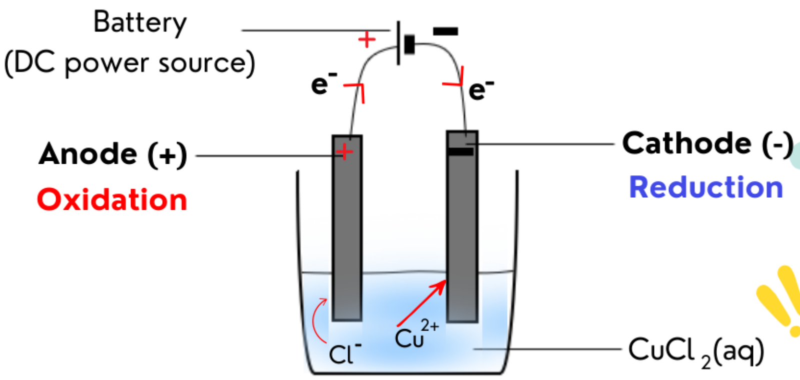


Figure 2

PRO - TIPS

A DC power source must be used in an electrolytic cell to ensure that the electrons flow in one direction only i.e., from the anode to the cathode.

Anions move towards the anode
Cations move towards the cathode

Through a process of electrolysis, the decomposition of copper (II) chloride takes place.

Definition: Electrolysis: The chemical process in which electrical energy is converted to chemical energy. **OR** the use of electrical energy to produce a chemical change.

Analysis of the electrolysis of copper (II) chloride

Reduction half reaction: $Cu^{2+} + 2e^- \longrightarrow Cu$
(from table 4A or table 4B)

Oxidation half reaction: $2Cl^- \longrightarrow Cl_2 + 2e^-$
(from table 4A or table 4B)

Balanced net reaction: $Cu^{2+} + 2Cl^- \longrightarrow Cu + Cl_2$

Observations

- Solid copper (reddish - brown in colour) is deposited at the cathode.
- A green chlorine gas bubbles at the anode.
- Due to the concentration of Cu^{2+} ions in solution decreasing, the initial blue solution decreases in colour.

Electroplating

What is electroplating?

Electroplating is the process of depositing a layer of one metal onto another metal.
The process of electrolysis takes place.

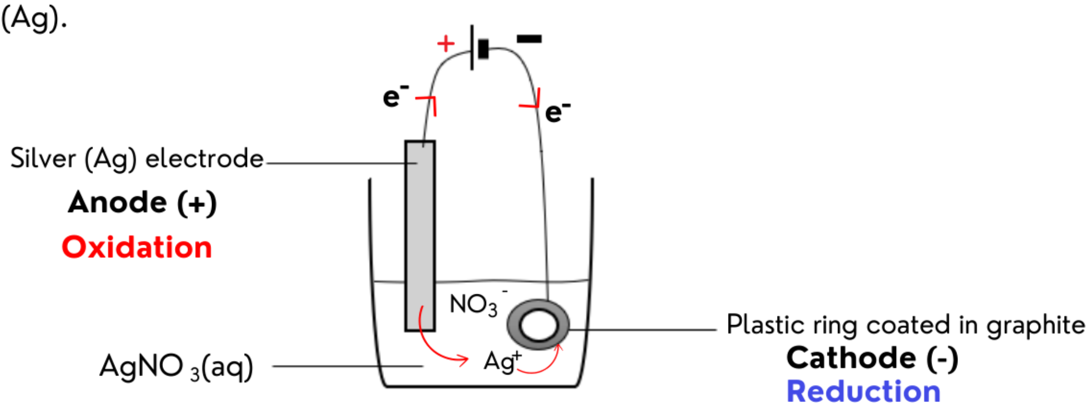
What is the purpose of electroplating?

Electroplating is used to improve the metals appearance, protect the metal or to give it other useful properties.

Process

- The object being electroplated (coated) must **undergo reduction** and is therefore the cathode (it is connected to the negative terminal of the battery).
- The object (metal **X**) doing the electroplating (i.e., the coating) must **undergo oxidation** and is therefore the anode (it is connected to the positive terminal of the battery).
- The electrolyte is a solution of a compound containing ions of the metal (metal **X**) doing the electroplating.

Example: A plastic ring (coated in graphite to ensure that it is conductive), is coated with silver(Ag).



Analysis of the electroplating of a plastic ring coated in graphite with silver

Oxidation half reaction: $Ag \rightarrow Ag^+ + e^-$
(from table 4A or table 4B)

Reduction half reaction: $Ag^+ + e^- \rightarrow Ag$
(from table 4A or table 4B)

Balanced net reaction: $Ag^+ + Ag \rightarrow Ag + Ag^+$

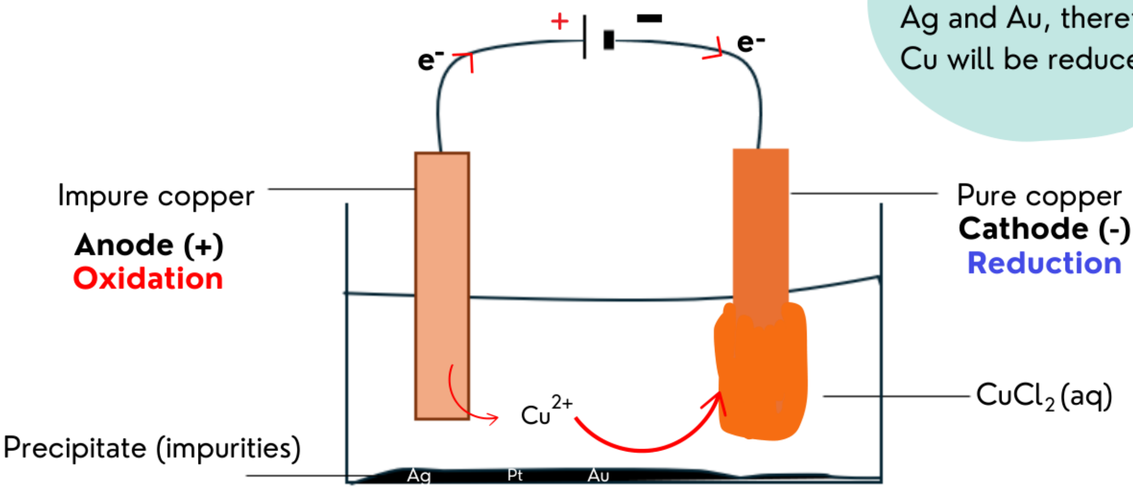
Refining of metals e.g., copper (electrorefining of copper)

- Electrorefining is used to purify copper. This is a very similar process to electroplating.
- The **impure copper** [which contains other metal impurities such as zinc (Zn),silver (Ag), platinum (Pt) and gold (Au)] is the **anode (+),** which is connected to the positive terminal of the battery and undergoes oxidation. These impure metals do **not** undergo oxidation, and form a solid precipitate at the bottom of the container. The anode decreases in mass.
- The **pure copper, the cathode (-),** which is connected to the negative terminal of the battery and undergoes reduction. The cathode increases in mass due to the pure copper being deposited onto the cathode.
- The electrolyte must be a solution containing **Cu^{2+} ions**.

Example: Impure copper undergoes electrorefining to produce pure copper.

PRO - TIPS

Cu is a **stronger** reducing agent than Pt, Ag and Au, therefore Cu will be reduced.



Analysis of the electrorefining of copper

Oxidation half reaction: $Cu \rightarrow Cu^{2+} + 2e^-$
(from table 4A or table 4B)

Reduction half reaction: $Cu^{2+} + 2e^- \rightarrow Cu$
(from table 4A or table 4B)

Balanced net reaction: $Cu^{2+} + Cu \rightarrow Cu + Cu^{2+}$

Electrolysis of a concentrated solution of sodium chloride (Chlor-alkali industry)

- In the Chlor - alkali industry, through the electrolysis of a concentrated solution of sodium chloride (NaCl), chlorine gas [Cl_2 (g)], hydrogen gas [H_2(g)] and NaOH (aq) is produced.
- A concentrated solution of sodium chloride (NaCl) is called brine.
- In the Chlor-alkali industry, a **membrane cell** is used which consists of an ion - exchange membrane.
- The ion - exchange membrane is selectively permeable and only allows cations (e.g., Na^+) to migrate through.

Figure 3 below represents the structure of the membrane cell used in the electrolysis of concentrated sodium chloride.

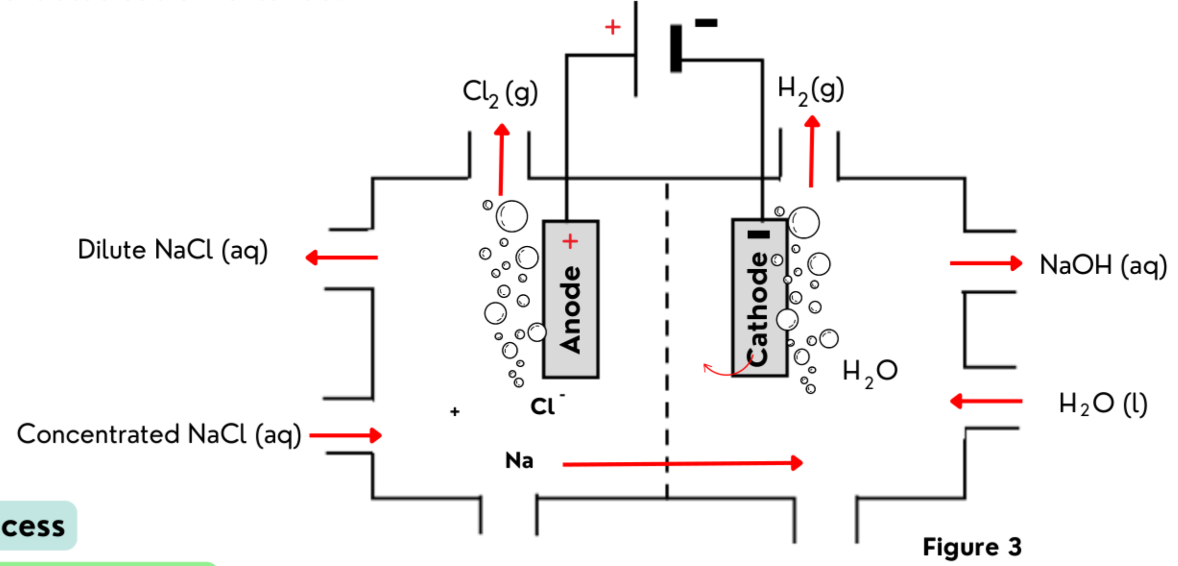


Figure 3

Process

At the anode (+)

- Concentrated sodium chloride (brine) is pumped into this cell compartment. The concentrated NaCl dissociates into Na^+(aq) and Cl^- (aq).
- The positive electrode (anode) attracts the negatively charged Cl^- ions in the solution.
- The Cl^- ions become oxidised and form Cl_2 (g)
- Oxidation half- reaction:$2Cl\ _2 \longrightarrow Cl^- + 2e^-$
  (From table 4A or table 4B)

At the cathode (-)

- Na^+ ions migrate through the ion - exchange membrane.
- Water (H_2O) is pumped into this component and partially ionises.
- There are H^+ions, Na^+ ions and H_2O molecules in this compartment.
- Due to Na^+ being a very weak reducing agent and the concentration of H^+ being very low, H_2O is reduced.
- Reduction half - reaction: $2H_2O + 2e^- \longrightarrow H_2 + 2OH^-$
  (from table 4A or table 4B)

Oxidation half reaction: $2Cl^- \longrightarrow Cl_2 + 2e^-$
(from table 4A or table 4B)

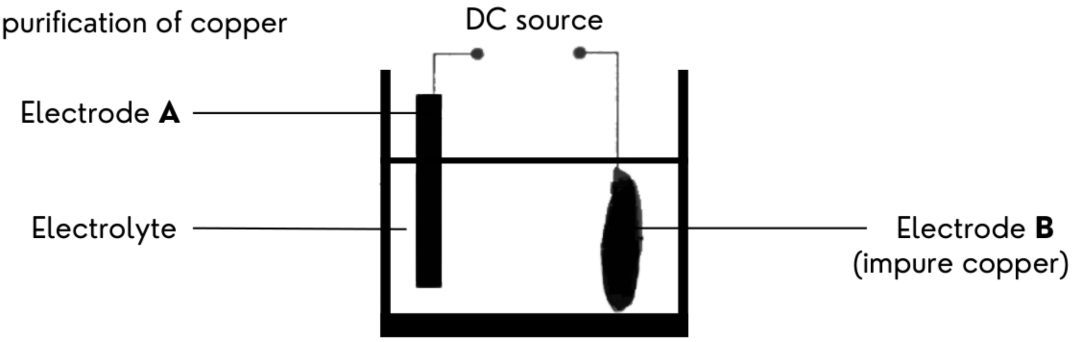
Reduction half reaction: $2H_2O + 2e^- \longrightarrow H_2 + 2OH^-$
(from table 4A or table 4B)

Balanced net reaction: $2H_2O + 2Cl^- \longrightarrow Cl_2 + H_2 + 2OH^-$

NOTE: The Na^+ ions are spectator ions in this reaction and bond to OH^- to form NaOH (aq)

Worked example

The simplified diagram below represents an electrochemical cell used for the purification of copper



1.1 Give a reason why a direct current (DC) source is used in this experiment. (2)

1.2 Write down the half reaction which takes place at electrode **A**. (2)

1.3 Due to small amounts of zinc impurities in the impure copper, the electrolyte becomes contaminated with Zn^{2+} ions.

Refer to the table of standard reduction potentials to explain why the Zn^{2+} ions will not affect the purity of the copper obtained in this experiment. (3)

1.4 After the purification of the impure copper was completed, it was found that $2,85 \times 10^{-2}$ moles of copper were formed.

The initial mass of electrode **B** was 2,0 g. Calculate the percentage impurities that was initially present in electrode **B**. (4)

1.1 A DC power source ensures that the electrons flow in one direction only i.e., from the anode to the cathode.

1.2
- In the electrolytic cell, electrode **B** (impure copper) is the anode, which undergoes oxidation.
- Electrode **A** is the pure copper and is the cathode. Reduction takes place at the cathode where the Cu^{2+} in solution are reduced.

Reduction half reaction: $Cu^{2+} + 2e^{-} \longrightarrow Cu$

1.3 To explain this answer, the strength of the oxidising agents in solution ($Zn^{2+}$and Cu^{2+}) must be **compared** and a conclusion drawn:

Zn^{2+} is weaker oxidising agent than Cu^{2+}, therefore the Cu^{2+} ions will be reduced to form Cu.

OR

Cu is a stronger oxidising agent than Zn^{2+} , therefore the Cu^{2+} ions will be reduced to form Cu.

1.4 OPTION 1

- The number of moles of pure copper formed in the reaction is known, using the formula $n = \frac{m}{M}$, the mass of pure copper formed can be determined.
- This mass of pure copper forms part of the total mass (2,0 g) of the impure copper (electrode **B**).
- To determine the mass of impurities, subtract the mass of pure copper from the total mass of electrode B.
- The percentage impurities can be determined by taking the mass of impurities divided by the total mass of electrode B and then converting this to a percentage by x 100.

n(pure Cu) = $\frac{m}{M}$
$(2,85 \times 10^{-2}) = \frac{m}{(63.5)}$
m(pure Cu) = 1,809...g

Mass of impurities = Total mass of electrode **B** – mass of pure Cu
Mass of impurities = 2 – 1,809...
Mass of impurities = 0,19...g

Percentage impurities = $\frac{0.19...}{2} \times 100$

Percentage impurities = 9,51 %

OR

OPTION 2

- The number of moles of pure copper formed in the reaction is known, using the formula $n = \frac{m}{M}$, the mass of pure copper formed can be determined.
- This mass of pure copper forms part of the total mass (2,0 g) of the impure copper (electrode **B**).
- The percentage purity can first be be determined by taking the mass of pure Cu divided by the total mass of electrode **B** and then converting this to a percentage by x 100.
- To determine the percentage impurities, subtract the percentage pure Cu from 100.

n(pure Cu) = $\frac{m}{M}$
$(2,85 \times 10^{-2}) = \frac{m}{(63.5)}$
m(pure Cu) = 1,809...g

Percentage pure Cu = $\frac{1.809...}{2} \times 100$

Percentage pure Cu = 90,487... %

Percentage impurities = 100 – 90,487...
Percentage impurities = 9,51 %