LEARNERS' ALLEY
Designed by Khow Willard

JC1

H2 Chemistry

Book 2

For the 9476 syllabus



NAME _____

9476 Scheme of Assessment

H2 Chemistry (Syllabus 9476, first examined in 2026). All candidates are required to enter for Papers 1, 2, 3 and 4.

Paper 1
Multiple Choice

DURATION	MARKS	WEIGHTING	TIME PER MARK
1 h	30	15%	2 min

- 30 compulsory multiple choice questions, each with 4 options.
- 5 to 8 of them are multiple completion questions.

Paper 2
Structured Questions

DURATION	MARKS	WEIGHTING	TIME PER MARK
2 h	75	30%	1.6 min

- A variable number of structured questions, all compulsory. Answers are written on the question paper.
- Includes data-based question(s) worth 20 to 25 marks in total.

Paper 3
Structured Questions

DURATION	MARKS	WEIGHTING	TIME PER MARK
2 h	75	35%	1.6 min

- **Section A** (55 marks): 3 to 4 compulsory structured questions of 15 to 25 marks each.
- **Section B** (20 marks): two 20-mark questions, answer **one**.

Paper 4
Practical

DURATION	MARKS	WEIGHTING	TIME PER MARK
2 h 30 min	50	20%	3 min

- **Planning**: 4% of the total.
- **Manipulation, measurement and observation**, **presentation of data and observations**, and **analysis, conclusions and evaluation**: 16% of the total.
- No books or laboratory notebooks may be used.

How to use these notes

Fill in the blanks

Write the missing key word on each line, e.g. electrons are added to the _____. The answers are the phrases examiners look for.

Labels

NOTE marks a special case, an exception or a point that is easy to miss. EXAM TIP marks advice on how to phrase an answer or set out working. ANSWER STRUCTURE shows how to set out the answer to a type of question you will meet again and again.

Explanations and examples

Numbered points in an explanation are separate mark points: write every one. Each WORKED EXAMPLE starts from a real exam question.

JC1 Book 2 Contents

9 — **Chemical Equilibria** — 46
1 Dynamic Equilibrium 2 Equilibrium Constants 3 Calculations with K 4 Le Chatelier's Principle 5 The Haber Process

11.1 — **Introduction to Organic Chemistry** — 50
1 Formulae of Organic Compounds 2 Terminology 3 Types of Organic Reactions 4 Hybridisation 5 Shapes and Bonding in Organic Molecules 6 Reagents and Bond Fission 7 Naming a Mechanism 8 Factors Affecting Reactivity 9 Isomerism

11.2 — **Alkanes** — 58
1 Structure and Naming 2 Physical Properties 3 Cracking 4 Reactivity and Combustion 5 Free Radical Substitution 6 Ratio of Products 7 Pollution from Combustion

11.3 — **Alkenes** — 62
1 Structure, Isomerism and Naming 2 Physical Properties 3 Preparation of Alkenes 4 Electrophilic Addition 5 Reactions of Alkenes 6 Oxidative Cleavage and Tests

11.4 — **Arenes** — 66
1 Structure of Benzene 2 Evidence for Delocalisation 3 Naming Arenes 4 Electrophilic Substitution 5 Effect of Substituents 6 Methylbenzene: Ring vs Side Chain

5 — **The Periodic Table** — 70
1 Organisation of the Periodic Table 2 Atomic and Ionic Radius 3 Electronegativity 4 First Ionisation Energy 5 Melting Point across Period 3 6 Electrical Conductivity across Period 3 7 Group 2 Elements 8 Oxides of Period 3 9 Chlorides of Period 3 10 Group 17: The Halogens 11 Hydrogen Halides 12 Deducing and Predicting

09 Chemical Equilibria

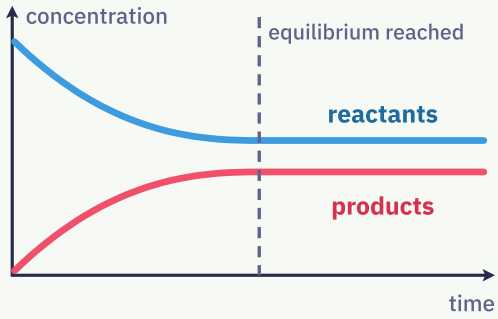


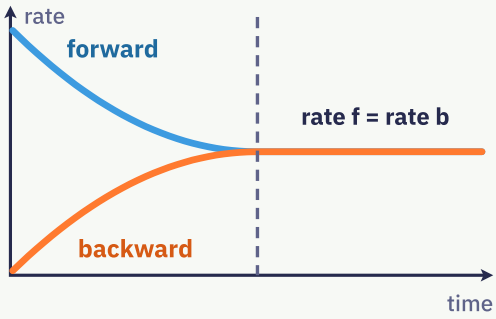
1 Dynamic Equilibrium

DEFINITION **Reversible reaction**: a reaction that takes place in both the _____ and _____ directions (⇌)

DEFINITION **Dynamic equilibrium**: the state in a reversible reaction where the rate of the forward reaction _____ the rate of the backward reaction, such that there is _____ in the concentrations of reactants and products, in a _____.

DEFINITION **Closed system**: no matter is lost to or gained from the surroundings





- At equilibrium, [reactants] and [products] are _____, but usually **not equal**, both reactions are still occurring
- The same equilibrium is reached whether we start from the reactants or the products
- In an open system, products _____, so the reaction goes to completion.

2 Equilibrium Constants

For $aA + bB \rightleftharpoons cC + dD$:

	Expression	Units	Use for
K_c	$\frac{[C]^c[D]^d}{[A]^a[B]^b}$	$(\text{mol dm}^{-3})^{(c+d)-(a+b)}$	species in solution or gas, as concentrations
K_p	$\frac{p_C{}^c\, p_D{}^d}{p_A{}^a\, p_B{}^b}$	$(\text{atm or Pa})^{(c+d)-(a+b)}$	_____, as partial pressures

- **Partial pressure**: $p_A = x_A \times p_{total}$, where the mole fraction $x_A = n_A \div n_{total}$
- **Heterogeneous** equilibria: leave out _____, _____ and the _____, as their concentrations are constant
- $CaCO_3(s) \rightleftharpoons CaO(s) + CO_2(g)$: K_c = _____, K_p = _____

NOTE K is changed **only by temperature**. Concentration, pressure and catalysts do not change K. K says nothing about how **fast** equilibrium is reached.

Size of K	Position of equilibrium	Equilibrium mixture
$K \gg 1$	lies to the _____	mostly products
$K \ll 1$	lies to the _____	mostly reactants

3 Calculations with K

ICE table: Initial, Change, Equilibrium. Convert equilibrium moles to concentration (÷ V) or partial pressure before substituting into K.

I: initial amounts → **C: change, in mole ratio** → **E: equilibrium amounts** → **÷ V (or p) → into K**

3.1 Find K_c from equilibrium amounts

WORKED EXAMPLE

$CH_3CO_2H(l) + C_2H_5OH(l) \rightleftharpoons CH_3CO_2C_2H_5(l) + H_2O(l)$

To make the ester ethyl ethanoate, 2.0 mol of ethanoic acid and 2.0 mol of ethanol are mixed. At equilibrium, 1.33 mol of water is present and the total volume is 0.500 dm³. Find K_c.

	CH_3CO_2H	C_2H_5OH	ester	H_2O
I / mol	2.0	2.0	0	0
C / mol	_____	−1.33	+1.33	+1.33
E / mol	0.67	0.67	1.33	1.33

Divide each by 0.500 dm³ to get concentrations:

$$K_c = \frac{(1.33/0.500)(1.33/0.500)}{(0.67/0.500)(0.67/0.500)} = \text{_____}\ \text{(no units)}$$

Water is a product here, not the solvent, so it is included. V cancels, but working must still show concentrations.

3.2 Find K_p from initial partial pressures

WORKED EXAMPLE

$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$

In the Contact process, SO_2 (1.00 atm) and O_2 (0.50 atm) reach equilibrium in a vessel of fixed volume at 675 K. The total pressure at equilibrium is 1.01 atm. Find K_p.

- At fixed volume and temperature, partial pressure ∝ moles, so the ICE table can use **pressures**
- Let **x** atm of O_2 react: SO_2 falls by **2x**, and SO_3 rises by **2x** (mole ratio 2 : 1 : 2)

	SO_2	O_2	SO_3
I / atm	1.00	0.50	0
C / atm	−2x	−x	+2x
E / atm	_____	_____	_____

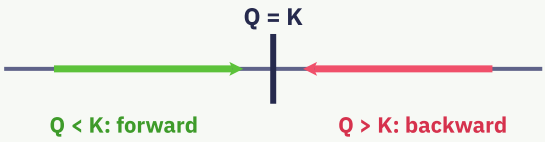
Total: $(1.00 - 2x) + (0.50 - x) + 2x = 1.01 \rightarrow x = 0.49$

$$K_p = \frac{p_{SO_3}^{\ 2}}{p_{SO_2}^{\ 2}\, p_{O_2}} = \frac{(0.98)^2}{(0.02)^2(0.01)} = \text{_____}$$

4 Le Chatelier's Principle

DEFINITION **Le Chatelier's Principle**: if a change is made to a system in dynamic equilibrium, the position of equilibrium shifts so as to _____ (minimise) that change and re-establish equilibrium.

- **$Q_c < K_c$**: too few products → _____ reaction favoured, POE shifts right
- **$Q_c = K_c$**: system is at _____, no net change
- **$Q_c > K_c$**: too many products → _____ reaction favoured, POE shifts left

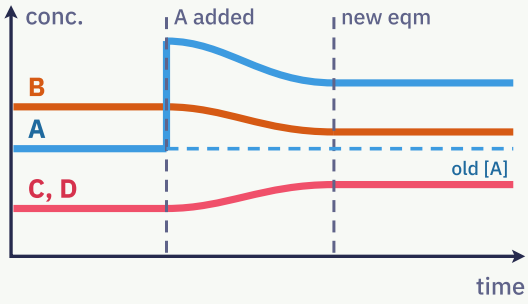


Q has the same expression as K but uses concentrations at any moment.

4.1 Concentration: $A + B \rightleftharpoons C + D$

Adding A

1. POE shifts _____ to consume some of the added A
2. Forward reaction is favoured
3. [A] ↓ (but stays higher than before), [B] ↓, [C] and [D] ↑
4. K_c _____

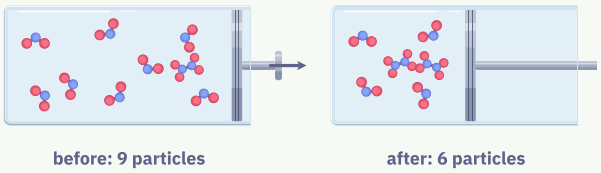


Removing a product, e.g. D: POE shifts right to produce more D.

4.2 Pressure: $2NO_2(g) \rightleftharpoons N_2O_4(g)$

Decreasing volume (pressure ↑)

1. Pressure ↑ → POE shifts to the side with _____ _____ to reduce the pressure
2. 2 mol gas → 1 mol gas: POE shifts _____
3. Brown colour becomes _____ (after first darkening as all gases are compressed)



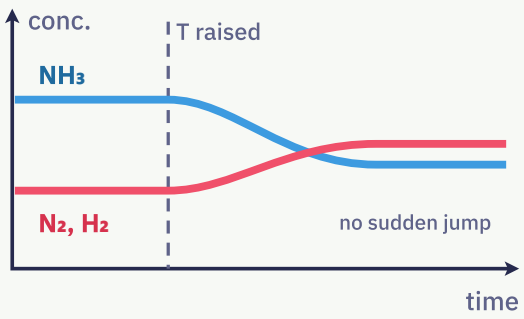
NOTE Special cases

- Equal moles of gas on both sides ($2HI \rightleftharpoons H_2 + I_2$): _____
- Inert gas at **constant volume**: partial pressures unchanged → no shift
- Inert gas at **constant pressure**: volume ↑, partial pressures ↓ → POE shifts to _____ gas particles

4.3 Temperature: $N_2 + 3H_2 \rightleftharpoons 2NH_3$, $\Delta H = -92$ kJ mol^{-1}

Increasing temperature

1. POE shifts _____
2. The _____ backward reaction is favoured to absorb the excess heat
3. $[NH_3]$ ↓ → K_c _____

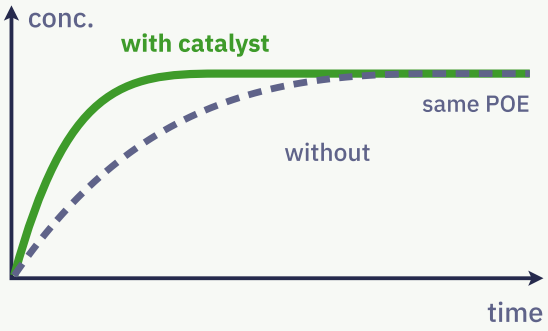


T ↑ favours the endothermic direction, T ↓ favours the exothermic direction. Only temperature changes K.

4 Le Chatelier's Principle (continued)

4.4 Catalyst

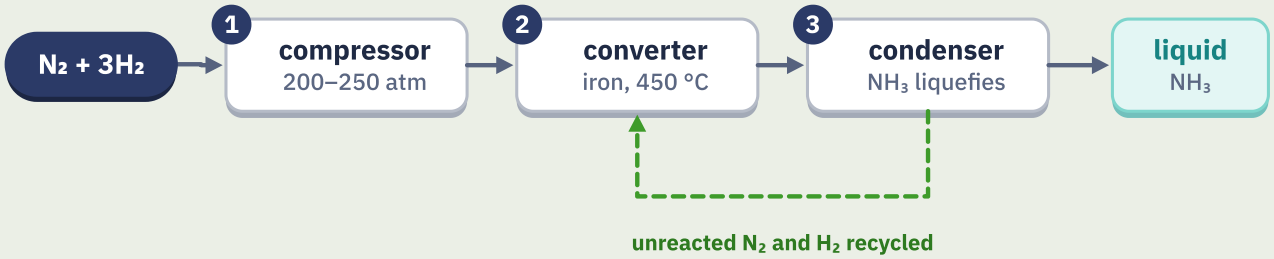
1. Rates of forward and backward reactions increase _____
2. E_a of both directions lowered by the same amount
3. k_f and k_b increase by the same factor
4. $K_c = \frac{k_f}{k_b}$ → no effect on POE or K
5. Equilibrium is only reached _____



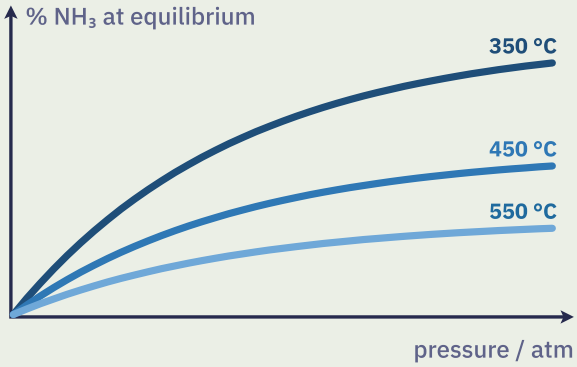
5 The Haber Process

$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g) \quad \Delta H = -92 \text{ kJ mol}^{-1}$$

The plant



Yield of NH_3 at equilibrium



- Yield of NH_3 at equilibrium **rises with pressure** and **falls with temperature**
- 200–250 atm and about 450 °C are a _____ between yield, rate and cost

Temperature: _____

- Forward reaction exothermic: low T shifts POE right → higher yield
- But at low T, rate is too _____
- Moderate T: reasonable yield in a reasonable time

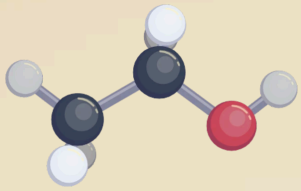
Pressure: _____

- 4 mol gas → 2 mol gas: high p shifts POE right → higher yield, also faster rate
- But very high p needs costly, thick-walled plant

Catalyst: _____

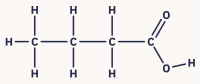
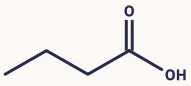
- Shortens the time to reach equilibrium, yield unchanged
- Cheaper than other catalysts (e.g. Ru)
- NH_3 is _____ _____ and removed: POE shifts right, unreacted N_2 and H_2 recycled

11.1 Introduction to Organic Chemistry



1 Formulae of Organic Compounds

Carbon forms many compounds: strong C–C bonds allow long chains and rings (catenation), C is tetravalent, allowing branching and multiple bonds.

Formula	Shows	Butanoic acid
Empirical	simplest _____ of atoms of each element	C_2H_4O
Molecular	_____ of atoms of each element in one molecule	$C_4H_8O_2$
Structural	how the atoms are joined, with minimal detail	$CH_3CH_2CH_2CO_2H$
Displayed	all atoms and _____. Bent (–O–H) and trigonal planar (C=O) groups must be drawn out with their shapes	
Skeletal	carbon skeleton and functional groups only, C and H on C not shown	
Stereochemical	3D arrangement: wedge = _____ the plane, dash = _____ the plane	

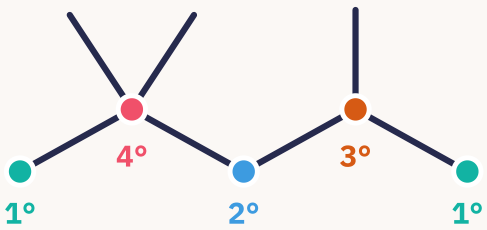
2 Terminology

DEFINITION **Hydrocarbon**: a compound containing _____

- **Functional group**: an atom or group of atoms responsible for the _____ of a compound
- **Alkyl group**, R: C_nH_{2n+1}, e.g. CH_3– methyl, C_2H_5– ethyl
- **Saturated**: only single bonds. **Unsaturated**: contains multiple bonds. Each π bond removes 2 H.
- **Homologous series**: a series of compounds with the same functional group, each member differing by $–CH_2–$. Its members have:
  - similar _____ reactions
  - similar methods of preparation
  - M_r increasing by _____ from one member to the next
  - a gradual change in _____ properties

2.1 Degree of substitution

A carbon bonded to _____ other carbons is primary (1°), secondary (2°), tertiary (3°) or quaternary (4°).



2,2,4-trimethylpentane

2 Terminology (continued)

2.2 Classes of compounds, in order of priority

Class	General	Group	Suffix	Prefix
carboxylic acid	RCO_2H	$-CO_2H$	**-oic acid**	–
ester	RCO_2R'	$-CO_2-$	**-oate**	alkoxy-carbonyl-
acyl chloride	RCOCl	–COCl	**-oyl chloride**	chloro-carbonyl-
amide	$RCONH_2$	–CONH–	**-amide**	–
nitrile	RCN	–C≡N	**-nitrile**	cyano-
aldehyde	RCHO	–CHO	**-al**	–
ketone	RCOR′	C=O	**-one**	–

Class	General	Group	Suffix	Prefix
alcohol	ROH	–OH	**-ol**	hydroxy-
phenol	ArOH	–OH	**phenol**	hydroxy-
amine	RNH_2, R_2NH, R_3N	–N	**-amine**	amino-
alkene	C_nH_{2n}	C=C	**-ene**	–
alkane	C_nH_{2n+2}	–	**-ane**	alkyl-
arene	$C_6H_5–R$	$C_6H_5–$	**-benzene**	phenyl-
halogeno-alkane	RX	–X	–	chloro-, bromo-, iodo-
amino acid	$RCH(NH_2)CO_2H$	$–NH_2$, $–CO_2H$	**-oic acid**	amino-

The highest group in the order gives the **suffix**, and every other group becomes a **prefix**: $HOCH_2CH_2CHO$ is 3-hydroxypropanal, $H_2NCH_2CO_2H$ is aminoethanoic acid. Halogens and alkyl groups are always prefixes, and C=C stays in the stem, as in but-3-en-1-ol.

An ester is named alkyl first, as in ethyl ethanoate: R′ (on O) must be an alkyl group, R may be H. The carbon of –C≡N and of –CHO counts in the stem, as in ethanenitrile, CH_3CN.

2.3 Naming organic compounds

No. of C	1	2	3	4	5	6	7	8	9	10
Stem	meth	eth	prop	but	pent	hex	hept	oct	non	dec

Steps

1. Find the **longest carbon chain** that contains the functional group: this gives the stem
2. **Number** the chain from the end that gives the functional group the lowest number
3. Name the **substituents** (methyl, chloro …) as prefixes with their positions, in alphabetical order (di-, tri- for repeats)
4. Add the **suffix** of the highest-priority functional group (table 2.2) with its position

Example: $CH_3CH(CH_3)CH_2OH$

1. Longest chain with the –OH: 3 C → _____
2. –OH on C1 → propan-1-ol
3. $–CH_3$ on C2 → _____

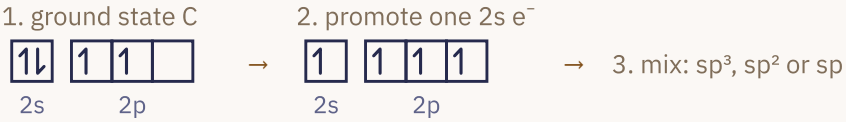
3 Types of Organic Reactions

Type	What happens	Example
Addition	two molecules combine to form _____ product, π bond broken	$CH_2=CH_2 + Br_2 \rightarrow CH_2BrCH_2Br$
Substitution	an atom or group is _____ by another	$CH_3CH_2Cl + OH^- \rightarrow CH_3CH_2OH + Cl^-$
Elimination	atoms removed from two _____ atoms to form a π bond	$CH_3CH_2OH \rightarrow CH_2=CH_2 + H_2O$
Condensation	two molecules join with loss of a _____ (H_2O, HCl)	$RCO_2H + R'OH \rightleftharpoons RCO_2R' + H_2O$
Hydrolysis	breaking of a bond by reaction with _____	$RCO_2R' + H_2O \rightleftharpoons RCO_2H + R'OH$
Oxidation	gain of O or loss of H, [O]	$CH_3CH_2OH + 2[O] \rightarrow CH_3CO_2H + H_2O$
Reduction	gain of H or loss of O, [H]	$CH_3COCH_3 + 2[H] \rightarrow CH_3CH(OH)CH_3$

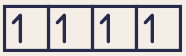
4 Hybridisation

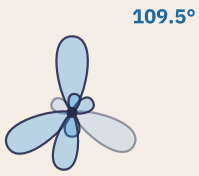
DEFINITION **Hybridisation**: the mixing of atomic orbitals in various combinations to give a set of _____ of equivalent energy for covalent bonding with other atoms.

Why hybridise? In its ground state C has only **two** unpaired electrons, yet in CH_4 it forms **four identical** bonds at 109.5°. So: one 2s electron is promoted, then the orbitals are mixed.



sp^3

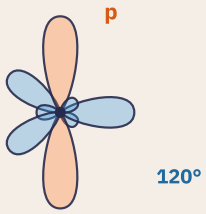




2s + three 2p mixed → 4 sp^3 orbitals
tetrahedral, _____, 4σ, 25% s
e.g. CH_4, ethane

sp^2

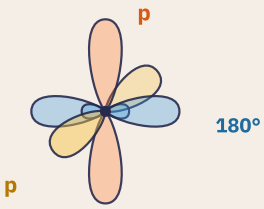




2s + two 2p mixed → 3 sp^2 + ____
trigonal planar, _____, 3σ + 1π, 33% s
e.g. ethene, benzene

sp





2s + one 2p mixed → 2 sp + ____
linear, _____, 2σ + 2π, 50% s
e.g. ethyne, CO_2

Each hybrid orbital has one large and one small lobe, the large lobe is used in bonding. Hybrid orbitals form σ bonds, unhybridised p orbitals form π bonds.

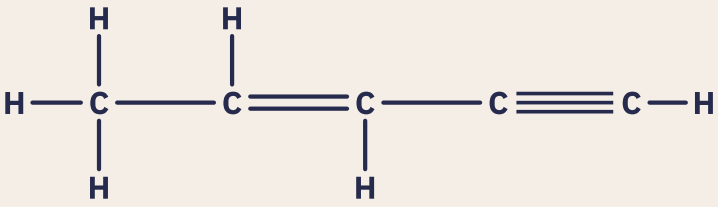
4.1 Hybridisation of each carbon atom

Count the regions of electron density around the C atom (a double or triple bond counts as _____ region):

Regions around C	Hybridisation	Shape
4 (all single bonds)	_____	tetrahedral
3 (one C=C or C=O)	_____	trigonal planar
2 (C≡C, or two C=C)	_____	linear

- Every single bond is **one σ** bond
- A double bond is **1σ + 1π**, a triple bond is **1σ + 2π**

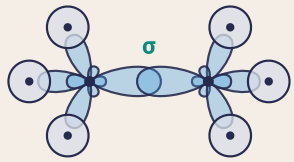
WORKED EXAMPLE For pent-3-en-1-yne, $CH_3CH{=}CHC{\equiv}CH$, state the hybridisation of each carbon atom and the number of σ and π bonds in one molecule.



C5 **sp^3** C4 **sp^2** C3 **sp^2** C2 **sp** C1 **sp**

1. C5 has 4 single bonds → sp^3, C4 and C3 each have one C=C → _____, C2 and C1 each have one C≡C → _____
2. σ bonds: 6 C–H + 4 C–C = ____
3. π bonds: 1 in C=C + 2 in C≡C = ____

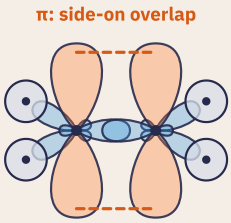
5 Shapes and Bonding in Organic Molecules



ethane (sp^3)

Ethane: each C is _____, tetrahedral, 109.5°, 4σ bonds

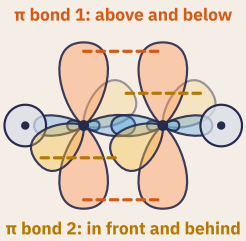
- C–H: head-on overlap of an **sp^3** orbital of C with the 1s orbital of H
- C–C: head-on overlap of an sp^3 orbital of each C



ethene (sp^2)

Ethene: each C is _____, trigonal planar, 120°, 3σ + 1π

- σ bonds: head-on overlap of sp^2 orbitals (and H 1s)
- π bond: _____ overlap of the unhybridised 2p orbital of each C, above and below the plane



ethyne (sp): two π bonds at 90°

Ethyne: each C is _____, linear, 180°, 2σ + 2π

- σ bonds: head-on overlap of sp orbitals (and H 1s)
- 2 π bonds: side-on overlap of the $2p_y$ orbitals and of the $2p_z$ orbitals, at _____ _____ to each other

Benzene: each C is sp^2, 120°, planar, the delocalised π system is covered in Arenes.

- **σ bond**: _____ overlap of hybrid orbitals (C–C) or of a hybrid orbital with H 1s (C–H)
- **π bond**: _____ overlap of unhybridised p orbitals, electron density above and below the plane

Why is C–H in ethene stronger than in ethane?

1. sp^2 orbital has more _____ than sp^3
2. → smaller orbital, electrons _____ _____
3. → more effective overlap, shorter and stronger bond

6 Reagents and Bond Fission

6.1 Types of reagent

Reagent	DEFINITION	Examples	Attacks
Nucleophile (Lewis base)	an _____, with a lone pair of electrons	OH^-, CN^-, Cl^-, NH_3, H_2O, ROH	an electron-poor centre, e.g. a $C^{\delta+}$ atom bonded to a halogen
Electrophile (Lewis acid)	an _____, electron deficient	H^+, NO_2^+, $Br^{\delta+}$–$Br^{\delta-}$, $H^{\delta+}$–Cl	an electron-rich centre, e.g. C=C or a benzene ring
Free radical	a species with an _____	Cl•, Br•, •CH_3	C–H bonds, e.g. in alkanes

NOTE A free radical is electron poor but is **not** an electrophile: an electrophile carries a partial or full positive charge.

6 Reagents and Bond Fission (continued)

6.2 Homolytic fission

The two bonding electrons are shared _____ : each atom takes one → two _____.



6.3 Heterolytic fission

The more electronegative atom takes _____ electrons → a cation and an anion. C^+ is a _____, C^- is a carbanion.



6.4 Drawing curly arrows

Where it starts and ends

An arrow starts at a **bond** or a **lone pair** and points to where the electrons go

Which way electrons flow

From _____ to _____ sites

The arrowhead

Full: a _____ of electrons moves. **Half** (fish-hook): _____ electron moves

What else to show

δ+ / δ−, lone pairs and charges on the species involved

7 Naming a Mechanism

ANSWER STRUCTURE mechanism name = attacking species + type of reaction

1. Look at the **first step**: what attacks the organic molecule? (nucleophile, electrophile or free radical)
2. Compare the **starting reactant** with the **final product** (ignore intermediates): is a group _____ (substitution) or are two molecules _____ (addition)?

Reaction	Attacked by	Mechanism
$CH_2{=}CH_2 + Br_2 \rightarrow CH_2BrCH_2Br$	$Br^{\delta+}$ attacks electron-rich C=C	_____
$CH_3CH_2Cl + OH^- \rightarrow CH_3CH_2OH + Cl^-$	OH^- attacks $C^{\delta+}$	_____
$CH_4 + Cl_2 \rightarrow CH_3Cl + HCl$ (UV)	Cl• attacks C–H	_____
$C_6H_6 + Br_2 \rightarrow C_6H_5Br + HBr$ ($FeBr_3$)	Br^+ attacks the benzene ring	electrophilic substitution

8 Factors Affecting Reactivity

8.1 Inductive effect

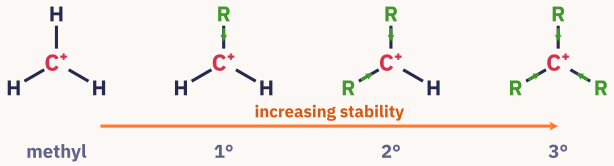
- **Electron-donating**: alkyl groups, increasing with size: $-CH_3 < -C_2H_5 < -CH(CH_3)_2 < -C(CH_3)_3$
- **Electron-withdrawing**: groups more electronegative than H, e.g. $-NO_2$, –Cl, –Br, –I
- The effect is stronger with **more** groups, and weaker the **further** the group is from the charge

	cation (+)	anion (–)
electron-donating	charge _____ → stabilised	charge intensified → destabilised
electron-withdrawing	charge intensified → destabilised	charge _____ → stabilised

8.2 Stability of carbocations

Why is a 3° carbocation more stable than a 1°?

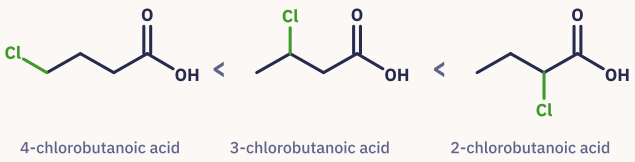
1. Alkyl groups are _____
2. → three alkyl groups _____ the positive charge on C^+ to a greater extent than one



8.3 Stability of anions and acid strength

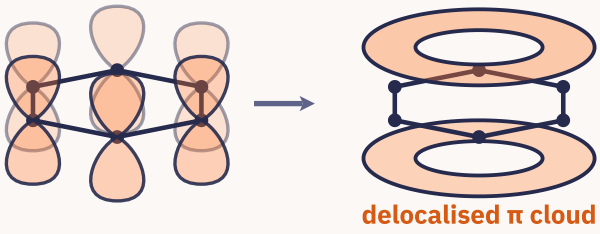
Arrange in increasing K_a:

1. –Cl is _____: it disperses the negative charge on the carboxylate ion
2. The _____ Cl is to $-CO_2^-$, the stronger the effect → more stable anion
3. → the acid dissociates more readily → larger K_a



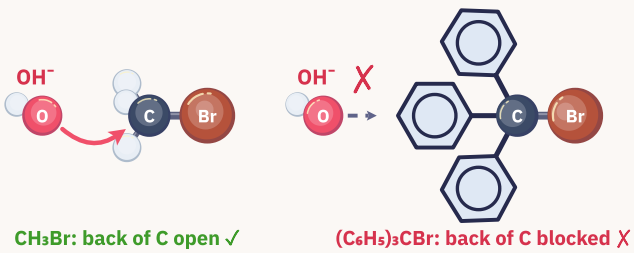
8.4 Delocalisation

When three or more adjacent p orbitals overlap, the π electrons spread over a _____ → the molecule gains extra _____, e.g. benzene.



8.5 Steric hindrance

Bulky groups near the reacting site _____ _____ of the attacking species and slow the reaction. E.g. OH^- must attack the C of C–Br from the side opposite Br: easy in CH_3Br with its small H atoms, but the three bulky benzene rings in $(C_6H_5)_3CBr$ block it.



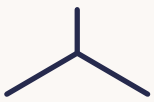
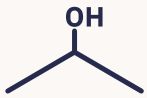
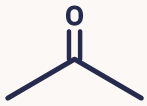
9 Isomerism

Isomers: compounds with the _____ but a different arrangement of atoms.

DEFINITION **Constitutional (structural) isomers**: molecules that have the same molecular formula but _____ _____. Types: chain, position and functional group.

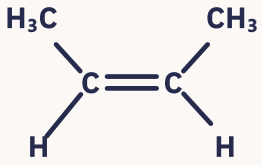
DEFINITION **Stereoisomers**: compounds that have the same molecular and structural formula, but differ in the _____ _____ of their atoms. Types: cis–trans isomers and enantiomers.

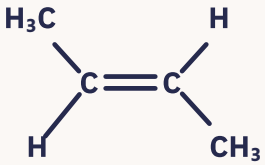
9.1 Constitutional (structural) isomerism

Type	The isomers differ in	Example
Chain	the _____ (branching)	 butane  2-methylpropane
Position	the _____ of the same functional group	 propan-1-ol  propan-2-ol
Functional group	the _____, e.g. an aldehyde and a ketone	 propanal  propanone

Each pair has one molecular formula: C_4H_{10}, C_3H_8O and C_3H_6O.

9.2 Cis–trans isomerism


cis-but-2-ene


trans-but-2-ene

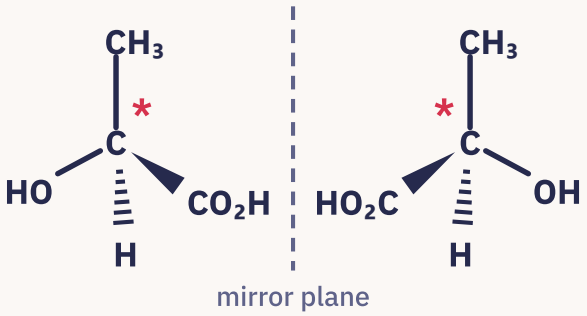
- Arises from _____ about the C=C bond: rotation would break the π bond, formed by side-on overlap of p orbitals
- Each C of the C=C must have _____ groups attached to it
- **cis**: the groups are on the same side of the C=C. **trans**: they are on opposite sides.

Physical properties of cis and trans isomers are in Topic 11.3.

9 Isomerism (continued)

9.3 Enantiomerism

- **Chiral centre**: a carbon atom bonded to _____ _____ atoms or groups, marked *
- **Chiral molecule**: a molecule that is not superimposable on its mirror image
- **Enantiomers**: a pair of molecules that are non-superimposable _____ of each other
- A molecule with a _____ is superimposable on its mirror image, so it is not chiral, even if it has chiral centres



EXAM TIP Draw a pair of enantiomers as mirror images on either side of a mirror plane, with two bonds in the plane, one wedge and one dash.

9.4 Properties of enantiomers

Property	Enantiomers are
Physical	_____, except the direction in which they rotate plane-polarised light (equal extent, opposite directions)
Chemical	_____, except in their interactions with another chiral molecule, e.g. an enzyme
Biological	often _____, e.g. in drug action, one enantiomer may treat the illness while the other is inactive or harmful

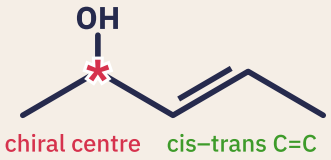
- **Optically active**: a sample that rotates plane-polarised light. It contains chiral molecules.
- **Racemic mixture**: equal proportions of both enantiomers. As each enantiomer rotates plane-polarised light to equal extents but in opposite directions, optical activity cancels out in the racemic mixture.

9.5 Deducing isomers

Steps

1. **Constitutional**: vary the _____, the _____ or the _____
2. **Cis–trans**: look for a C=C with _____ _____ groups on each C
3. **Enantiomers**: look for carbons with _____ _____ groups, the chiral centres
4. **Count**: stereoisomers = _____, n = chiral centres + C=C showing cis–trans (fewer if there is a plane of symmetry)

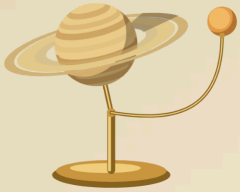
Worked example: pent-3-en-2-ol



$CH_3CH{=}CHCH(OH)CH_3$ has one chiral centre and one C=C that shows cis–trans isomerism. n = 1 + 1 = 2, so 2^2 = **4** stereoisomers.

EXAM TIP To find chiral centres in a skeletal formula, ignore the bends and the ends, as they cannot carry four different groups. Only look at the intersections.

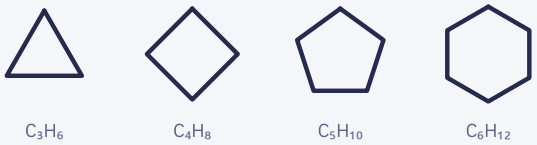
11.2 Alkanes



1 Structure and Naming

1.1 The alkane homologous series

- **Alkanes**: _____ hydrocarbons, C_nH_{2n+2}. Every C is _____, tetrahedral, 109.5°.
- **Cycloalkanes**: closed rings, C_nH_{2n} (same general formula as alkenes)

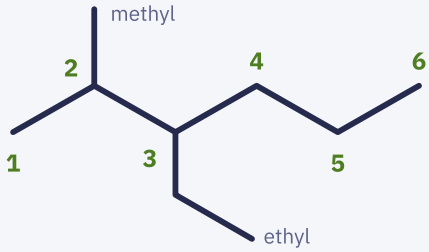


n	Name	Structural formula	n	Name	Structural formula
1	methane	CH_4	4	butane	$CH_3(CH_2)_2CH_3$
2	ethane	CH_3CH_3	5	pentane	$CH_3(CH_2)_3CH_3$
3	propane	$CH_3CH_2CH_3$	6	hexane	$CH_3(CH_2)_4CH_3$

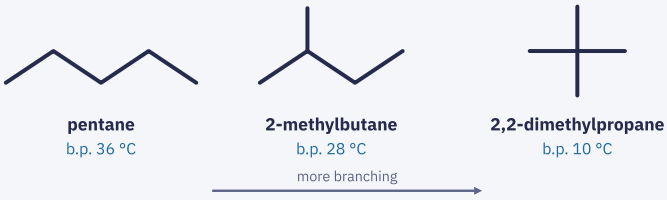
1.2 Naming a branched alkane

1. Find the _____ continuous carbon chain (parent name)
2. Number from the end _____ the first branch
3. Name substituents with locants, in _____ order (ignore di-, tri-)

3-ethyl-2-methylhexane: 6-carbon main chain, numbered from the left so the branches get the lowest locants. "Ethyl" comes before "methyl".



1.3 Structural isomers of C_5H_{12}



pentane
b.p. 36 °C

2-methylbutane
b.p. 28 °C

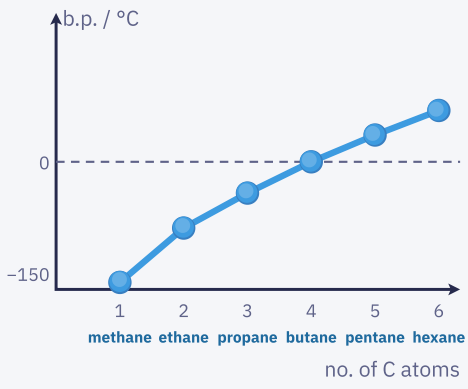
2,2-dimethylpropane
b.p. 10 °C

more branching

Same molecular formula, different structural formula. Alkanes with 4 or more C show branching isomerism.

2 Physical Properties

C–H bonds are essentially _____ → molecules held by weak _____ interactions.



1. b.p. increases with the number of C atoms

1. No. of electrons ↑ → larger, more _____ electron cloud
2. → stronger id–id → more energy needed to overcome them

2. Branched isomers have lower b.p.

1. More branching → more spherical, smaller _____ _____
2. → weaker id–id → less energy needed to overcome them

pentane 36 °C > 2-methylbutane 28 °C > 2,2-dimethylpropane 10 °C

2 Physical Properties (continued)

2.1 Solubility

Soluble in non-polar solvents (e.g. CCl_4). **Insoluble in water**:

1. Energy released from forming _____ interactions between alkane and water
2. is _____ to overcome the id–id between alkane molecules and the _____ between water molecules

2.2 Density and viscosity

Less dense than water

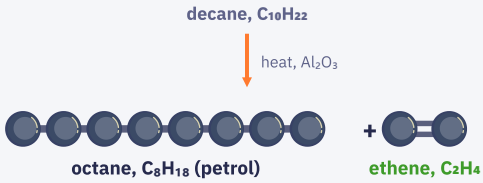
1. Molecules are held by weaker _____ than the hydrogen bonds between water molecules
2. → molecules are _____

- Density and viscosity ↑ with M_r: stronger id–id draws molecules closer
- More branching → poorer packing → lower density

3 Cracking

DEFINITION **Cracking**: the breaking down of _____ alkanes into shorter-chain alkanes and _____, using heat and a catalyst.

- Conditions: high temperature, Al_2O_3 or SiO_2 catalyst (catalytic cracking)
- Meets demand for petrol and gives alkenes for making polymers



4 Reactivity and Combustion

Why are alkanes unreactive?

1. C–H bonds are _____: no electron-rich or electron-poor sites to attract nucleophiles or electrophiles
2. C–C and C–H bonds are _____

They react only with O_2 (combustion) and halogens (free radical substitution).

- **Complete** (excess O_2): $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$, $\Delta H = -890$ kJ mol^{-1}
- **Incomplete** (limited O_2): $2CH_4 + 3O_2 \rightarrow$ _____ $+ 4H_2O$, or C (soot)
- Alkanes burn as **gases**, higher alkanes are less volatile and burn with **sooty** flames

4.1 Identify a hydrocarbon from combustion data

WORKED EXAMPLE 15 cm³ of a gaseous hydrocarbon is burnt completely in 100 cm³ of O_2. 60 cm³ of CO_2 forms and 10 cm³ of O_2 is left over (same conditions). Find its formula.

$$C_xH_y(g) + \left(x + \frac{y}{4}\right)O_2(g) \rightarrow xCO_2(g) + \frac{y}{2}H_2O(l)$$

1. 1 mol C_xH_y gives x mol CO_2:

$x = \frac{60}{15} =$ ____

2. O_2 used = 100 − 10 = 90 cm³:

$x + \frac{y}{4} = \frac{90}{15} = 6$

3. $4 + \frac{y}{4} = 6 \rightarrow y =$ _____

$\therefore$ _____

5 Free Radical Substitution

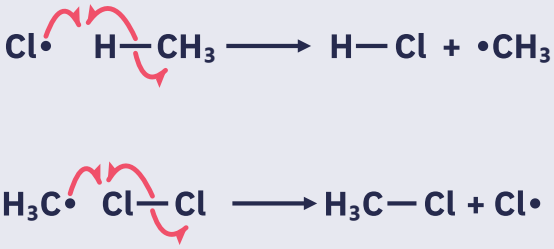
$CH_4 + Cl_2 \rightarrow CH_3Cl + HCl$ Cl_2 or Br_2, _____ or heat (250–400 °C)

Step 1: Initiation



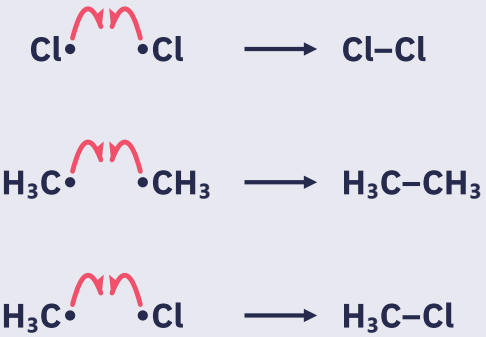
UV breaks Cl–Cl _____ to give a low concentration of Cl•. Use half arrows.

Step 2: Propagation



Cl• is _____, so the reaction is a chain reaction

Step 3: Termination



Two radicals combine, so radicals are _____ and not regenerated

EXAM TIP Write at least **two** termination steps. Show the • on the radical carbon (CH_3CH_2•).

5.1 Common explanations for FRS

- **Why does Cl–Cl break, not C–H?** BE(Cl–Cl) = 244 kJ mol^{-1} is the _____ bond, UV light does not supply enough energy to break C–H (410 kJ mol^{-1})
- **Why is no H• formed?** Cl• + CH_4 → •CH_3 + HCl has ΔH = _____ kJ mol^{-1}, but Cl• + CH_4 → CH_3Cl + H• has ΔH = +70 kJ mol^{-1}, so it is _____
- **Why does the reaction continue after the UV light is removed?** Each propagation step _____ a radical, so the chain continues until termination uses up the radicals

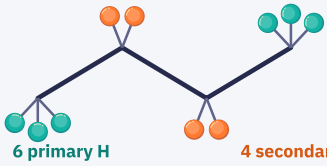
5.2 Different conditions for FRS

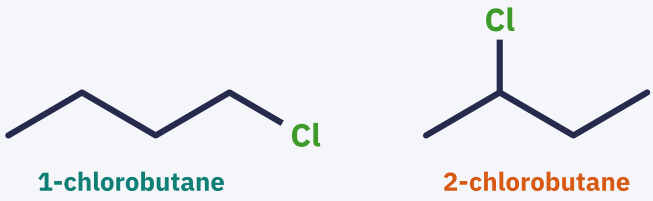
- **Limited Cl_2** (excess alkane): mainly _____ substitution, as Cl• is more likely to collide with CH_4
- **Excess Cl_2**: _____ substitution: CH_2Cl_2, $CHCl_3$, CCl_4
- A mixture of products forms → poor for synthesis

F_2	Cl_2, Br_2	I_2
_____	UV light or heat	_____ (ΔH = +22)

6 Ratio of Products

6.1 Statistical ratio





1-chlorobutane **2-chlorobutane**

If every H atom were _____ to be replaced by Cl, the ratio of products would equal the ratio of the numbers of H atoms that give each product.

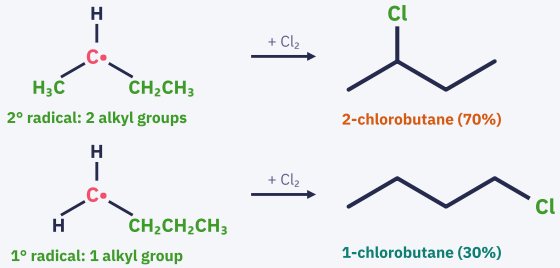
1. Butane has 6 primary H (on the two CH_3) and 4 secondary H (on the two CH_2)
2. Replacing a primary H gives 1-chlorobutane, replacing a secondary H gives 2-chlorobutane
3. ∴ statistical ratio 1-chlorobutane : 2-chlorobutane = 6 : 4 = _____

Propane: 6 primary : 2 secondary H = 3 : 1 for 1- : 2-chloropropane. 2-methylpropane: 9 primary : 1 tertiary H = 9 : 1.

6.2 Experimental ratio

Experimentally **30 : 70**: more 2-chlorobutane forms than the statistical ratio predicts. Why?

1. The intermediate that forms 2-chlorobutane is a _____: the electron-deficient radical is stabilised by _____ electron-donating alkyl groups
2. The intermediate that forms 1-chlorobutane is a primary radical, which is less stable, as it is stabilised by only 1 electron-donating alkyl group
3. ∴ formation of 2-chlorobutane is favoured due to the more _____



Radical stability: methyl < 1° < 2° < 3°. The more electron-donating alkyl groups on the radical carbon, the more stable the radical.

7 Pollution from Combustion

- **CO**: binds _____ more strongly than O_2 → less O_2 carried
- **Unburnt hydrocarbons**: form photochemical smog
- **NO_x**: high engine temperature breaks N≡N, $N_2 + O_2 \rightarrow 2NO$. Causes smog, low-level O_3, and acid rain via $NO_2 + SO_2 \rightarrow SO_3 + NO$
- **CO_2, CH_4**: greenhouse gases → enhanced greenhouse effect

Catalytic converter: Pt, Pd, Rh (redox)

Removing CO and NO

$2CO + 2NO \rightarrow 2CO_2 + N_2$

CO is _____ to CO_2, NO is _____ to N_2.

Removing unburnt hydrocarbons

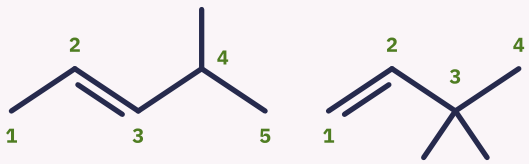
hydrocarbons + $NO_x \rightarrow CO_2 + H_2O + N_2$

11.3 Alkenes

1 Structure, Isomerism and Naming

1.1 Structure and naming

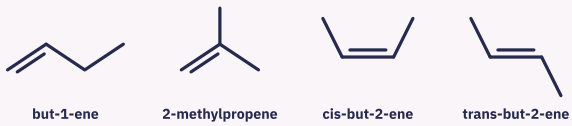
- **Alkenes**: _____ hydrocarbons with a C=C bond, C_nH_{2n}. Each C of C=C is sp^2, trigonal planar, 120°.
- **Naming**: longest chain **containing** the C=C, number from the end giving C=C the _____ locant, e.g. $CH_3CH{=}CHCH_2CH_3$ is pent-2-ene



Substituents take the numbering fixed by the C=C: **4-methylpent-2-ene**, **3,3-dimethylbut-1-ene**. Name cis or trans as drawn.

1.2 Isomers of C_4H_8

- **Chain** and **position** isomers: structural isomers
- **Cis–trans** isomers: due to _____ about C=C (the π bond would have to break). Each C of C=C must have _____ groups.



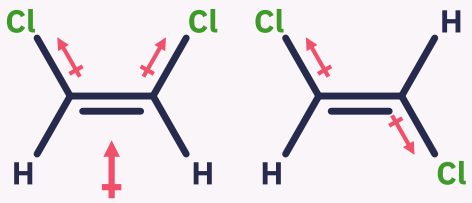
Why is trans more stable than cis?

1. In the cis isomer, the bulky groups are on the _____
2. → greater _____ (repulsion) between them

2 Physical Properties

Similar to alkanes: non-polar, held by **id–id**, insoluble in water, less dense than water, b.p. rises with chain length and falls with branching.

2.1 cis isomers have a higher b.p.



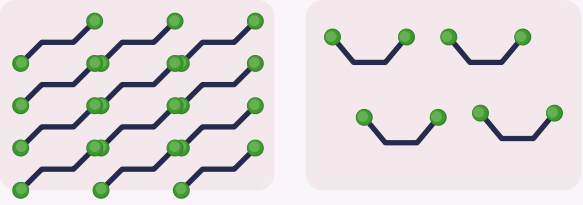
cis: μ > 0
net dipole

trans: μ = 0
dipoles cancel

1. cis has a _____ moment (polar), in trans the dipoles cancel
2. → additional _____ between cis molecules → more energy to overcome

2.2 cis isomers have a lower m.p.

1. cis has _____ (U-shape)
2. → molecules _____ less closely in the solid
3. → weaker IMF in the lattice → less energy to overcome



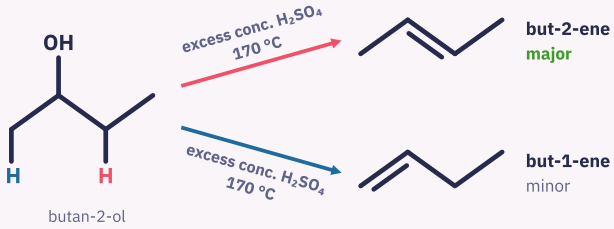
trans: packs closely

cis: gaps, weaker IMF

3 Preparation of Alkenes

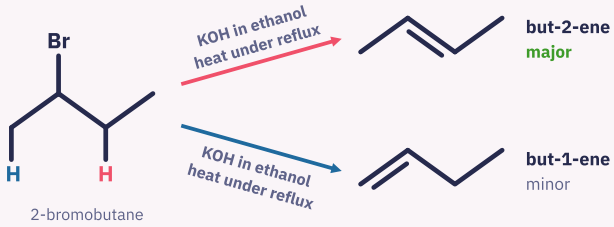
3.1 Dehydration of alcohols

- Elimination of H_2O: _____ at 170 °C, or pass the vapour over heated _____
- If the OH carbon has different neighbouring C–H groups, **more than one** alkene can form



3.2 Elimination of HX from halogenoalkanes

- Elimination of HX: _____, heat under reflux
- Major product: the _____ alkene (more alkyl groups on the C=C carbons), which is _____

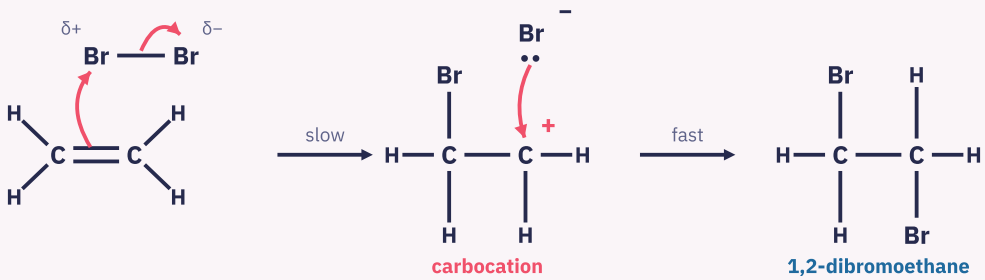


4 Electrophilic Addition

Why do alkenes react with electrophiles?

1. The C=C has a high _____, the π electrons lie above and below the plane and are _____
2. → attracts electron-deficient species: one weak π bond broken, two σ bonds formed

4.1 Mechanism: $CH_2{=}CH_2 + Br_2$ in CCl_4, room temperature



Step 1 (slow)

The π electrons _____ in Br_2 and attack $Br^{\delta+}$, Br–Br breaks **heterolytically** → carbocation + Br^-

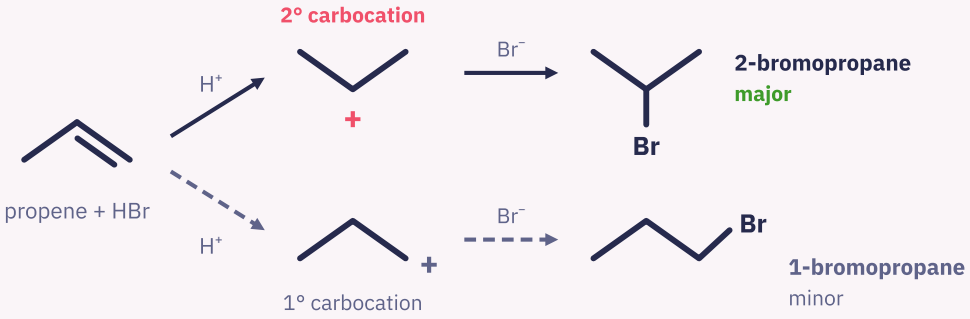
Step 2 (fast)

The lone pair on Br^- is donated to the C^+ atom.

ANSWER STRUCTURE **Describe the mechanism** Name it (electrophilic addition), then draw it with reagents and conditions, δ+/δ−, lone pairs, charges and curly arrows. No written explanation is needed.

4 Electrophilic Addition (continued)

4.2 Markovnikov's rule: propene + HBr



The rule

H adds to the C=C carbon with _____ _____, so the more stable 2° carbocation forms → 2-bromopropane is **major**.

Why is the 2° carbocation more stable?

1. Alkyl groups are _____
2. → two alkyl groups _____ the positive charge more than one

Reactivity of HX: HI > HBr > HCl (H–X bond strength decreases).

5 Reactions of Alkenes

Reaction	Equation, with reagents and conditions on the arrow (propene)	Observation
+ HX	$CH_3CH{=}CH_2 + HBr \xrightarrow{HBr(g),\ r.t.} CH_3CHBrCH_3$	–
+ X_2	$CH_3CH{=}CH_2 + Br_2 \xrightarrow{Br_2 \text{ in } CCl_4,\ r.t.} CH_3CHBrCH_2Br$	orange-red Br_2 _____
+ X_2(aq)	$CH_3CH{=}CH_2 + Br_2 + H_2O \xrightarrow{Br_2(aq),\ r.t.} CH_3CH(OH)CH_2Br + HBr$	orange decolourises
+ H_2O	$CH_3CH{=}CH_2 + H_2O \xrightarrow{\text{steam, }_____\text{, 300 °C, 60 atm}} CH_3CH(OH)CH_3$	–
+ H_2	$CH_3CH{=}CH_2 + H_2 \xrightarrow{Ni,\ heat\ (or\ _____,\ r.t.)} CH_3CH_2CH_3$	–
mild [O]	$CH_3CH{=}CH_2 + [O] + H_2O \xrightarrow{_____\ KMnO_4,\ NaOH(aq)} CH_3CH(OH)CH_2OH$	purple decolourises, _____ MnO_2
strong [O]	$CH_3CH{=}CH_2 + 5[O] \xrightarrow{KMnO_4,\ H_2SO_4(aq),\ _____} CH_3CO_2H + CO_2 + H_2O$	purple decolourises

Hydration can also use cold conc. H_2SO_4, then warm water. With Br_2(aq), the bromohydrin is major as H_2O (the solvent) is present in far larger amount than Br^-.

6 Oxidative Cleavage and Tests

Hot acidified $KMnO_4$ breaks C=C. Each half becomes:

Half of C=C	Product
$=CH_2$ (terminal)	_____
=CHR	_____, RCO_2H
=CRR′	_____, RCOR′

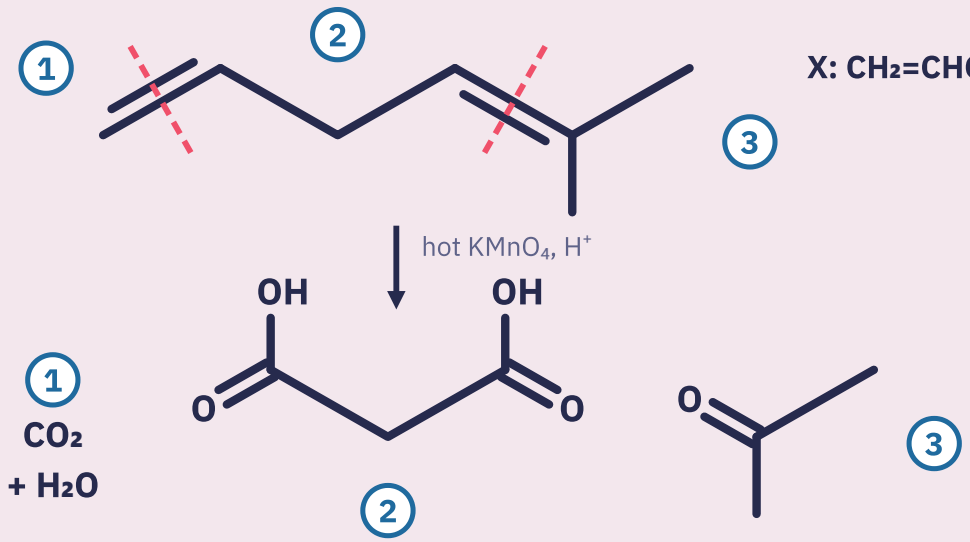
Split C=C, add =O to each C, then replace any –H on that C by –OH.

Test for C=C: add Br_2(aq) or Br_2 in CCl_4 at r.t. → orange _____.

Test for a terminal alkene (=CH₂): heat with acidified $KMnO_4$ → purple $KMnO_4$ _____, and a colourless, odourless gas forms that gives a _____ with limewater (CO_2 from the $=CH_2$).

6.1 Identify the alkene

WORKED EXAMPLE Hydrocarbon X, C_7H_{12}, is heated with acidified $KMnO_4$. The only organic products are CO_2, propanone and propanedioic acid, $HO_2CCH_2CO_2H$. Deduce the structure of X.



1. Piece 1: CO_2 → from a terminal _____
2. Piece 3: propanone, $(CH_3)_2C{=}O$ → from _____
3. Piece 2: $HO_2CCH_2CO_2H$ (two $–CO_2H$) → from _____, a C=C at each end
4. Join the pieces at the C=C: X is _____, 5-methylhexa-1,4-diene (C_7H_{12} ✓)

11.4 Arenes

1 Structure of Benzene

1.1 Kekulé structure and the real structure



Kekulé structures (do not exist) ≠ real structure

Shape

C_6H_6: _____ regular hexagon, all bond angles 120°

Bond lengths

All C–C bonds are _____ in length (0.139 nm), between C–C and C=C

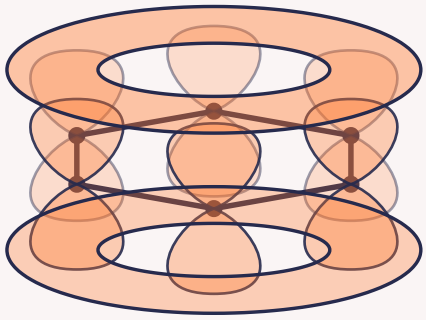
Drawing it

The Kekulé structure (cyclohexatriene) does not exist, the real molecule is drawn with a **circle**

1.2 Delocalisation in benzene

1. Each C is _____ hybridised: it forms three σ bonds (two C–C and one C–H)
2. The unhybridised _____ on each C, containing one electron, is _____ to the plane of the ring
3. Each p orbital overlaps _____ with both neighbours → a continuous ring of 6 delocalised π electrons _____ the ring

π cloud above the ring



and below

1.3 Why is benzene less reactive than an alkene towards electrophiles?

1. In benzene, the π electrons are _____ over six C atoms, so the electron density is _____ than in the localised π bond of C=C
2. → electrophiles are less strongly attracted, reaction also needs the loss of delocalisation in the intermediate → higher E_a, so a catalyst or stronger electrophile is needed

2 Evidence for Delocalisation

2.1 Enthalpy change of hydrogenation

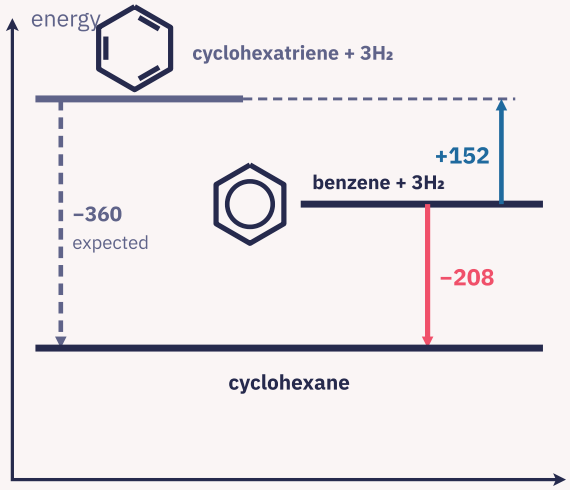
Expected vs actual

Expected for 3 C=C: 3 × (−120) = −360 kJ mol⁻¹

Actual: _____ kJ mol⁻¹

Delocalisation energy

Benzene is _____ kJ mol⁻¹ more stable than cyclohexatriene.



2.2 Bond lengths

Bond	Length / nm
C–C in cyclohexane	0.154
C–C in benzene	_____
C=C in cyclohexene	0.133

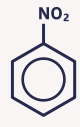
The C–C bond length in benzene lies **between** a single and a double bond: each bond has partial double bond character, as the π electrons are delocalised over all six bonds.

2.3 Substitution, not addition

Reagent	Cyclohexene	Benzene
Br_2 in CCl_4, dark	addition	no reaction
HBr(g)	addition	no reaction

Addition would destroy the delocalised π system and its extra stability, substitution _____ it.

3 Naming Arenes



nitrobenzene



methylbenzene



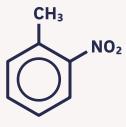
phenol



benzoic acid



benzaldehyde



2-nitro-methylbenzene

- C_6H_5– is **phenyl**, $C_6H_5CH_2$– is **benzyl**. An alkyl group with more than 6 C: name as phenylalkane (2-phenylheptane).
- **Traditional name**: some groups give the compound a special name, e.g. phenol (–OH), benzoic acid (–CO_2H), benzaldehyde (–CHO), methylbenzene (–CH_3). That group is at **C1**, number the other substituents from it and list them alphabetically.

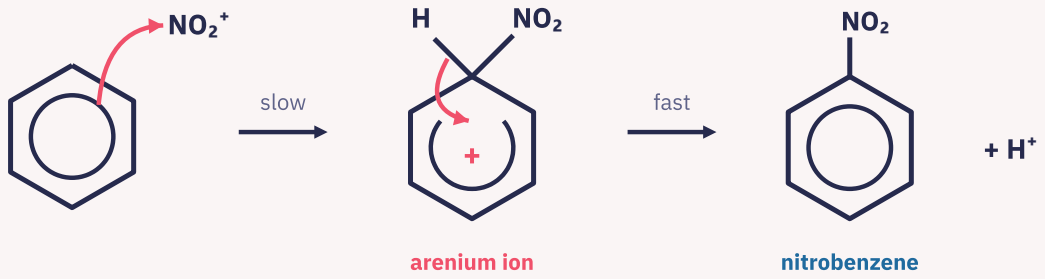
4 Electrophilic Substitution

The delocalised π cloud is a region of _____ → attacked by electrophiles, substitution keeps the ring's stability.

4.1 Mechanism: electrophilic substitution (nitration of benzene)

Reagents and conditions: conc. HNO_3, conc. H_2SO_4, 50 °C

$$HNO_3 + 2H_2SO_4 \rightarrow _____ + 2HSO_4^- + H_3O^+$$



$$H^+ + HSO_4^- \rightarrow H_2SO_4$$

ANSWER STRUCTURE **Describe the mechanism** Name it (electrophilic substitution), write the equation that forms the electrophile, draw every step perfectly with reagents and conditions, curly arrows, the arenium ion and charges, then write the equation that regenerates the catalyst. Write the equations only: no headings such as "forming the electrophile" and no written explanation.

Reaction	Reagents and conditions	Electrophile formed
Nitration	_____, 50 °C (methylbenzene 30 °C, deactivated 70 °C)	NO_2^+
Halogenation	X_2, _____ (or Fe), r.t., dark	$X_2 + FeX_3 \rightarrow X^+ + FeX_4^-$
Friedel–Crafts alkylation	RCl, _____ or $FeCl_3$, r.t.	$RCl + AlCl_3 \rightarrow R^+ + AlCl_4^-$
Friedel–Crafts acylation	RCOCl, _____, heat under reflux	$RCOCl + AlCl_3 \rightarrow RCO^+ + AlCl_4^-$



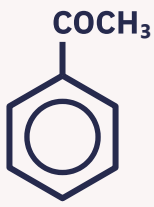
nitrobenzene



chlorobenzene



methylbenzene (R = CH_3)

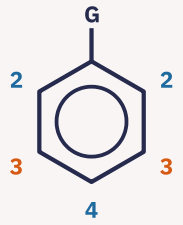


phenylethanone (RCO = CH_3CO)

FeX_3 and AlX_3 are Lewis acids, regenerated at the end: $H^+ + FeX_4^- \rightarrow HX + FeX_3$. Anhydrous, as they react with water.

5 Effect of Substituents

5.1 Effect on reactivity



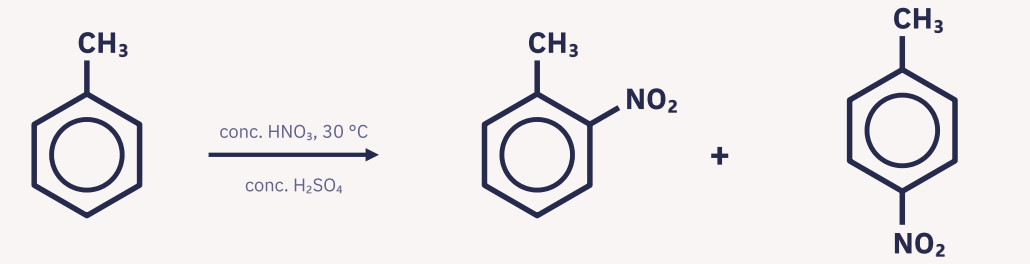
Ring-activating group, e.g. $-CH_3$

1. $-CH_3$ is _____: increases the electron density of the ring → ring more attractive to electrophiles
2. and _____ the carbocation intermediate → faster than benzene

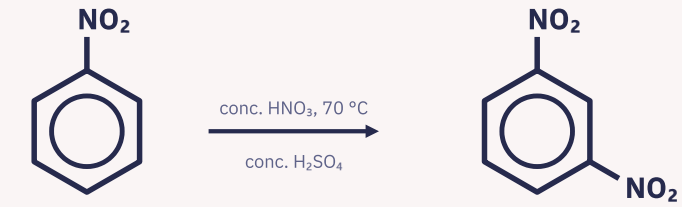
Ring-deactivating group, e.g. $-NO_2$

1. $-NO_2$ is _____: decreases the electron density of the ring → ring less attractive to electrophiles
2. and _____ the carbocation intermediate → slower than benzene

5.2 Directing effect: where the second group goes



methylbenzene — 2-nitromethylbenzene — 4-nitromethylbenzene



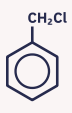
nitrobenzene — 1,3-dinitrobenzene

Activating, 2,4-directing
$-CH_3$, $-OH$, $-NH_2$, $-OR$. Electron-donating, e.g. phenol + dil. HNO_3 → 2- and 4-nitrophenol

Deactivating, 3-directing
$-NO_2$, $-CN$, $-CO_2H$, $-CHO$, $-COR$. Electron-withdrawing, slower than benzene

Deactivating, 2,4-directing
Halogens: withdraw by induction, but the lone pair stabilises the 2,4-intermediates

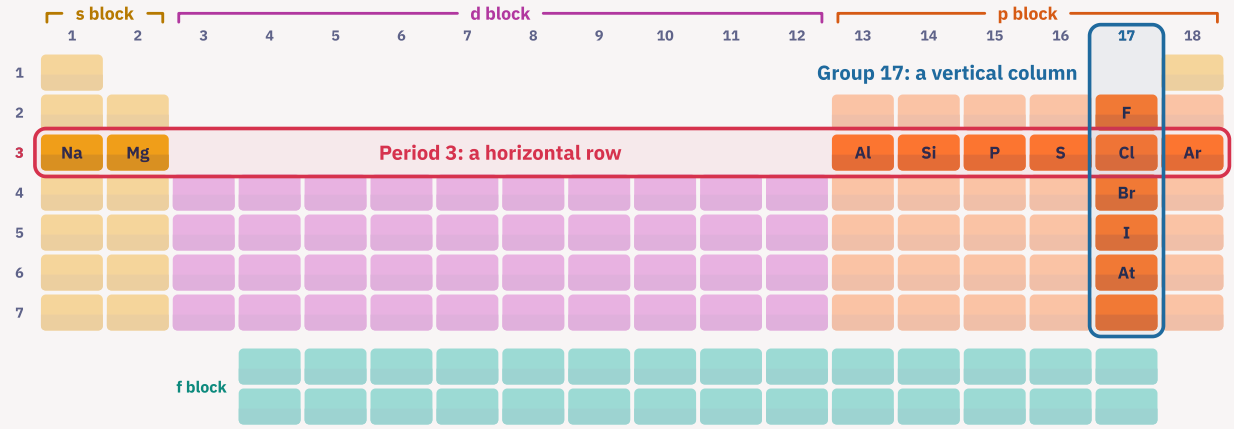
6 Methylbenzene: Ring vs Side Chain

Reaction of methylbenzene	Reagents and conditions	Product	Notes
Ring: electrophilic substitution	Cl_2, _____, r.t., _____		at the 2- and 4-positions ($-CH_3$ is 2,4-directing)
Side chain: free radical substitution	Cl_2, _____		further substitution gives $-CHCl_2$ and $-CCl_3$
Side-chain oxidation	$KMnO_4$, dil. H_2SO_4, _____ or $KMnO_4$, OH^-, heat, then H^+		benzoic acid (white ppt on cooling), needs a _____

Any alkyl side chain with a benzylic H is oxidised to $-CO_2H$ (ethylbenzene also gives CO_2). tert-Butylbenzene has no benzylic H: no reaction. $K_2Cr_2O_7$ is too weak.

05 The Periodic Table

1 Organisation of the Periodic Table



s block p block d block f block Period 3 Group 17

- **Periodicity**: the _____ of physical and chemical properties at regular intervals, with elements in order of increasing proton number
- Blocks are named after the subshell holding the valence electrons
- **Group** (column): same outer electronic configuration → similar _____ properties. Main group: group number = no. of valence electrons
- **Period** (row): period number = principal quantum number, n, of the _____

2 Atomic and Ionic Radius

2.1 Atomic radius

Atomic radius: half the distance between the nuclei of two adjacent atoms of the same element.

Across Period 3, atomic radius ↓

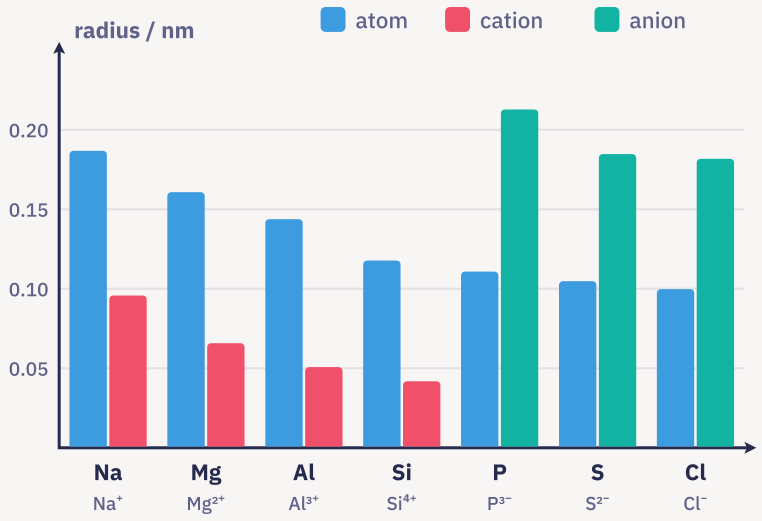
1. Nuclear charge ↑, electrons added to the _____ → shielding approx. constant
2. → stronger attraction between nucleus and valence electrons

Down a group, atomic radius ↑

1. Number of filled _____ _____ ↑
2. → valence electrons further from nucleus and more shielded → weaker attraction

2 Atomic and Ionic Radius (continued)

2.2 Ionic radius



Cation is smaller than its atom

1. Atoms lose some or all of their _____ to form cations
2. → cations usually have _____ principal quantum shell of electrons

Anion is larger than its atom

1. Electrons are added to the outermost principal quantum shell to form anions
2. → greater _____ _____ in the outermost shell

Isoelectronic ions: Na^+ → Si^{4+} and P^{3-} → Cl^-

1. Isoelectronic ions have the _____ _____
2. Atomic number ↑ → nuclear charge ↑ → ionic radius ↓

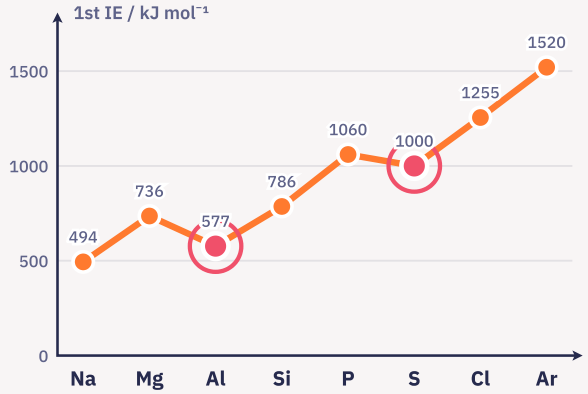
NOTE **P^{3-} ≫ Si^{4+}**: P^{3-} has one _____ filled principal quantum shell.

3 Electronegativity

DEFINITION **Electronegativity**: the ability of an atom to _____ of electrons in a covalent bond.

- **Across** a period ↑: nuclear charge ↑, shielding approx. constant
- **Down** a group ↓: more shells, bonding pair further and more shielded
- Across Period 3, the electronegativity difference with O or Cl ↓ → oxides and chlorides change from _____ to _____

4 First Ionisation Energy



General trend: first IE ↑ across Period 3

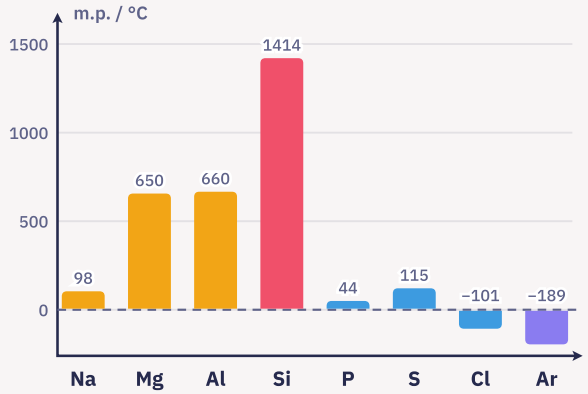
1. Nuclear charge ↑, shielding approx. constant (same shell)
2. → more energy to remove the more strongly attracted valence electron

Down a group: IE ↓ (more shells, more shielding)

Exceptions: the two dips

- **Mg → Al**: 3p e^- removed is higher in energy than 3s
- **P → S**: _____ between the paired 3p e^- in S → one of them is easier to remove than an unpaired 3p e^- from P

5 Melting Point across Period 3



Element	Structure	m.p.
Na, Mg, Al	_____	high, ↑ across
Si	_____	highest
P_4, S_8, Cl_2	_____	low
Ar	monatomic	lowest

Na < Mg < Al

More valence e^- delocalised per atom and smaller, higher-charged cation → stronger _____

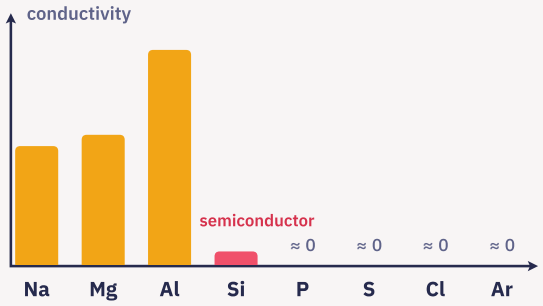
Si

A very large amount of energy is needed to break the extensive network of strong _____

S_8 > P_4 > Cl_2 > Ar

No. of electrons in S_8 > P_4 > Cl_2 > Ar → more energy is needed to overcome the stronger _____ between S_8 molecules than between P_4, then Cl_2 molecules, then Ar atoms

6 Electrical Conductivity across Period 3



1. **Na → Al**: _____ lattice, high conductivity from mobile delocalised electrons
2. Conductivity ↑ Na → Al, as more _____ _____ per atom are delocalised
3. **Si**: sharp drop, giant molecular _____, conducts more as T ↑
4. **P_4 → Ar**: simple molecular or atoms, essentially zero, as there are _____

7 Group 2 Elements

7.1 Reducing power

Reducing power: the ability of an element to lose electrons and reduce another species. Group 2 metals react as $M \rightarrow M^{2+} + 2e^-$.

Why does reducing power ↑ down the group?

1. Down the group, the number of principal quantum shells ↑ → atomic radius ↑
2. Shielding effect ↑, which _____ the increase in nuclear charge
3. → valence e^- _____ by the nucleus → less energy is needed to remove them
4. ∴ M loses its 2 valence e^- more readily → reducing power ↑
5. $E\ominus(M^{2+}/M)$ more negative down the group: Mg −2.38, Ca −2.87, Ba −2.90 V

Examples of differing reducing power: reaction with water

- **Mg**: reacts very slowly with cold water, but readily with steam: $Mg + H_2O(g) \rightarrow MgO + H_2$
- **Ca, Sr, Ba**: react with cold water, increasingly vigorously down the group: $M + 2H_2O \rightarrow M(OH)_2 + H_2$. Solutions become more alkaline

NOTE Group 2 elements only form the +2 state: removing a third e^- means removing an e^- from an inner shell.

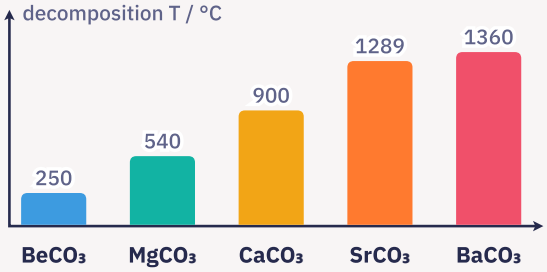
7.2 Thermal stability of carbonates

Thermal stability: the resistance of a compound to decomposition on heating. The thermal stability of Group 2 carbonates _____ down the group.

$$MCO_3(s) \rightarrow MO(s) + CO_2(g)$$

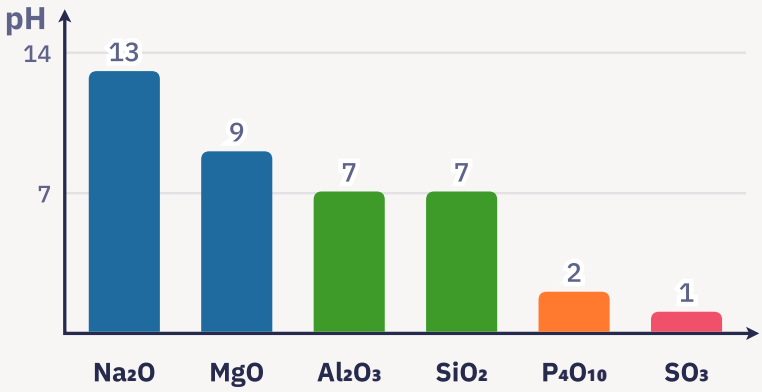
Why does thermal stability ↑ down the group?

1. Down the group, the radius of the metal cation ↑ and its _____ ↓
2. → the ability of M^{2+} to _____ the electron cloud of the large CO_3^{2-} anion ↓, and the C–O bonds are weakened to a smaller extent
3. ∴ more energy is needed to decompose MCO_3 → thermal stability ↑



8 Oxides of Period 3

8.1 Structure, bonding and nature



Oxide	Ox. no.	Structure and bonding	Nature	pH in water
Na_2O	**+1**	giant ionic	_____	**13**
MgO	**+2**	giant ionic	basic	**9**
Al_2O_3	**+3**	giant ionic, _____	_____	**7 (insoluble)**
SiO_2	**+4**	giant molecular	acidic	**7 (insoluble)**
P_4O_{10}	**+5**	simple molecular	acidic	**2**
SO_3	**+6**	simple molecular	acidic	_____

8.2 Equations, in order of the elements

Oxide	With water	With acid	With alkali
Na_2O	$Na_2O + H_2O \rightarrow 2NaOH$	$Na_2O + 2HCl \rightarrow 2NaCl + H_2O$	–
MgO	$MgO + H_2O \rightleftharpoons Mg(OH)_2$	$MgO + 2HCl \rightarrow MgCl_2 + H_2O$	–
Al_2O_3	no reaction	$Al_2O_3 + 6HCl \rightarrow 2AlCl_3 + 3H_2O$	$Al_2O_3 + 2OH^- + 3H_2O \rightarrow$ _____
SiO_2	no reaction	–	$SiO_2 + 2OH^- \rightarrow$ _____ $+ H_2O$ hot, concentrated NaOH
P_4O_{10}	$P_4O_{10} + 6H_2O \rightarrow$ _____	–	$P_4O_{10} + 12OH^- \rightarrow 4PO_4^{3-} + 6H_2O$
SO_3	$SO_3 + H_2O \rightarrow$ _____	–	$SO_3 + 2OH^- \rightarrow SO_4^{2-} + H_2O$

EXAM TIP Reactions with water and alkali are not redox: the oxidation number stays the same, so P_4O_{10} (+5) gives H_3PO_4 (+5), not H_3PO_3.

8.3 Why is Al_2O_3 amphoteric?

1. Al^{3+} is small and highly charged → high _____
2. → _____ the electron cloud of O^{2-} → partial covalent character
3. ∴ reacts with both acids and bases

$Al(OH)_3$ is amphoteric too: $Al(OH)_3 + 3H^+ \rightarrow Al^{3+} + 3H_2O$ and $Al(OH)_3 + OH^- \rightarrow [Al(OH)_4]^-$. NaOH and $Mg(OH)_2$ are basic only.

8 Oxides of Period 3 (continued)

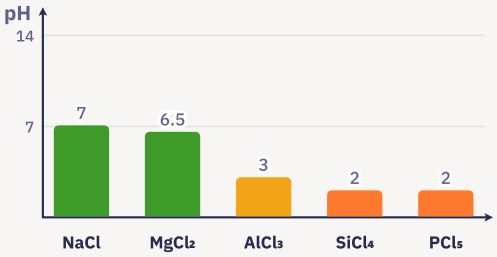
8.4 Why are Al_2O_3 and SiO_2 insoluble?

- **Al_2O_3**: very high _____
- **SiO_2**: extensive network of strong _____
- Not enough energy is released on hydration to overcome these, so pH stays 7

9 Chlorides of Period 3

9.1 Structure and behaviour in water

Chloride	Ox. no.	Structure	With water	pH
NaCl	**+1**	giant ionic	hydration only	**7**
$MgCl_2$	**+2**	giant ionic	hydration, _____ hydrolysis	**6.5**
$AlCl_3$ (Al_2Cl_6)	**+3**	simple molecular	hydration, _____ hydrolysis	**3**
$SiCl_4$	**+4**	simple molecular	_____ hydrolysis	**2**
PCl_5	**+5**	simple molecular	complete hydrolysis	**2**



Highest oxidation number = no. of valence e^-, as every valence e^- is used in bonding to the more electronegative O or Cl: +1 (Na) to +6 (S in SO_3).

9.2 Equations, in order of the elements

Chloride	Excess water	Limited water
NaCl	$NaCl(s) \rightarrow Na^+(aq) + Cl^-(aq)$	–
$MgCl_2$	$MgCl_2 + 6H_2O \rightarrow [Mg(H_2O)_6]^{2+} + 2Cl^-$ $[Mg(H_2O)_6]^{2+} \rightleftharpoons [Mg(H_2O)_5(OH)]^+ + H^+$	–
$AlCl_3$	$AlCl_3 + 6H_2O \rightarrow [Al(H_2O)_6]^{3+} + 3Cl^-$ $[Al(H_2O)_6]^{3+} \rightleftharpoons [Al(H_2O)_5(OH)]^{2+} + H^+$	$AlCl_3 + 3H_2O \rightarrow Al(OH)_3 + 3HCl$ white solid, white fumes
$SiCl_4$	$SiCl_4 + 2H_2O \rightarrow$ _____	–
PCl_5	$PCl_5 + 4H_2O \rightarrow$ _____	$PCl_5 + H_2O \rightarrow POCl_3 + 2HCl$

9.3 Why is $AlCl_3(aq)$ acidic?

1. Al^{3+} has a high _____
2. → strongly _____ the O–H bonds of the water ligands
3. → O–H weakens and breaks, releasing H^+

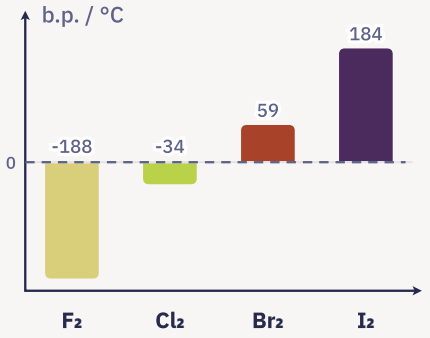
9.4 Why does $SiCl_4$ hydrolyse but not CCl_4?

- **Si** has _____ to accept a lone pair from H_2O
- **C** has no 3d orbitals, and the small C atom is _____ by four large Cl atoms

10 Group 17: The Halogens

10.1 Physical properties

	At r.t.p.	In hexane	In water	X–X / kJ mol^{-1}
F_2	pale yellow gas	very pale yellow	–	**158**
Cl_2	greenish-yellow gas	pale yellow	pale yellow	**244**
Br_2	red-brown liquid	_____	orange	**193**
I_2	black solid	_____	brown	**151**



NOTE F–F is weaker than Cl–Cl: the lone pairs on the two small, close F atoms repel each other.

10.2 Volatility

Volatility: the ease with which a substance changes into a gas. The lower the b.p., the more volatile the substance.

Why does volatility ↓ down the group?

1. All halogens are simple molecular, non-polar X_2 molecules
2. Down the group, M_r ↑ → no. of electrons ↑ → electron cloud more _____ → stronger id–id
3. → _____ is needed to overcome the id–id between X_2 molecules → b.p. ↑ → volatility ↓

10.3 Oxidising power

Oxidising power: the ability of an element to gain electrons and oxidise another species. Halogens react as $X_2 + 2e^- \rightarrow 2X^-$.

Why does oxidising power ↓ down the group?

1. Down the group, the number of principal quantum shells ↑ → atomic radius ↑
2. Shielding effect ↑, which _____ the increase in nuclear charge
3. → the incoming e^- is _____ by the nucleus → X_2 gains electrons less readily
4. ∴ oxidising power ↓: $F_2 > Cl_2 > Br_2 > I_2$
5. $E^{\ominus}(X_2/X^-)$ less positive down the group: F_2 +2.87, Cl_2 +1.36, Br_2 +1.07, I_2 +0.54 V

10.4 Displacement reactions: each halogen with the other halide ions

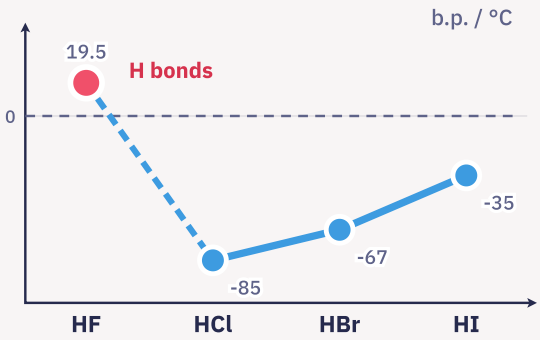
A halogen oxidises the halide ions of the halogens **below** it. Observations are for aqueous solutions, shaking with hexane shows the halogen formed more clearly.

Halogen	Halide	Reaction	Observation
F_2	Cl^-, Br^-, I^-	oxidises all of them	F_2 also oxidises water, so it is not used in aqueous solution
Cl_2	Br^-	$Cl_2 + 2Br^- \rightarrow 2Cl^- + Br_2$	colourless solution turns _____, orange-red in hexane
Cl_2	I^-	$Cl_2 + 2I^- \rightarrow 2Cl^- + I_2$	colourless solution turns _____, purple in hexane
Br_2	Cl^-	no reaction	solution stays orange (from Br_2)
Br_2	I^-	$Br_2 + 2I^- \rightarrow 2Br^- + I_2$	orange solution turns _____, purple in hexane
I_2	Cl^-, Br^-	no reaction	solution stays brown (from I_2)

11 Hydrogen Halides

11.1 Boiling points

- **HCl → HI**: more electrons → stronger _____ → b.p. ↑
- **HF**: anomalously high, due to _____



11.2 Thermal stability

HX	H–X / kJ mol⁻¹	On heating
HF	**562**	stable
HCl	**431**	stable
HBr	**366**	some _____ Br_2 fumes
HI	**299**	_____ I_2 fumes with a hot rod

Why does thermal stability decrease down the group?

1. Valence orbital of X is _____ → less effective overlap with H 1s
2. → H–X bond _____ → less energy needed to break it

12 Deducing and Predicting

12.1 Identify element X

X is a solid with very low conductivity at r.t. Its only chloride is a liquid non-conductor, which hydrolyses in water to give a white solid and a strongly acidic solution.

ANSWER STRUCTURE Set out each piece of information beside what you deduce from it, then conclude.

Information	Deduction
solid, very low conductivity	_____
chloride is a liquid non-conductor	_____ chloride
white solid + strongly acidic solution	$SiCl_4 + 2H_2O \rightarrow SiO_2 + 4HCl$

∴ X is _____

12.2 Predict: astatine, below iodine

Prediction	Reason
less electronegative than I	more shells, more shielding
dark solid, less volatile	more electrons, stronger _____
HAt decomposes more easily	H–At bond _____ than H–I
cannot oxidise Cl^- to Cl_2	weaker _____ than I_2