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IB DIPLOMA CHEMISTRY · FIRST ASSESSMENT 2025

Structure 3.2 Functional Groups

Booklet 4 · Understandings 3.2.1 – 3.2.4

How organic molecules are drawn, how functional groups sort them into classes, and why the members of a homologous series show trends in their boiling and melting points

Complete revision notes & memory points · Standard Level & Higher Level

How the level tags work in this booklet

SL + HL **Core material.** Understandings 3.2.1 to 3.2.4 are common to both levels. Every student must know all of it.

HL Short HL panels: hybridization and the shapes it gives carbon (section 2.7), the condensation of two amino acids to form a dipeptide (section 3.6) and a look ahead to spectroscopy. SL students can skip these panels and the questions marked HL.

Inside this booklet

1. What the syllabus actually asks of you
2. 3.2.1 — Representing organic molecules
3. 3.2.2 — Functional groups and classes
4. 3.2.3 — Homologous series
5. 3.2.4 — Trends in physical properties
6. Key points to memorise
7. Check yourself
8. Answers

1 What the syllabus actually asks of you

The guiding question for Structure 3.2 is: *how does the classification of organic molecules help us to predict their properties?* Many millions of carbon compounds are known, and new ones are made every day, so nobody could learn them one at a time. Instead, chemists sort them into **classes** by the **functional group** they contain. A small group of atoms such as –OH or –COOH gives every compound in its class similar chemical reactions, and the length of the carbon chain fine-tunes the physical properties in a predictable way. Before you can classify a molecule, though, you have to be able to read and draw it, so this booklet starts with the different kinds of formula.

Understanding	What it says	What you must be able to do	Level
3.2.1 Formulas	Organic compounds can be represented by different types of formula: empirical, molecular, structural (full and condensed), stereochemical and skeletal.	Identify the different formulas, and interconvert molecular, skeletal and structural formulas. Construct 3D models (real or virtual) of organic molecules. Stereochemical formulas are not expected to be drawn, except where specifically indicated.	SL + HL
3.2.2 Functional groups	Functional groups give characteristic physical and chemical properties to a compound. Organic compounds are divided into classes according to the functional groups present.	Identify these functional groups by name and structure: **halogeno, hydroxyl, carbonyl, carboxyl, alkoxy, amino, amido, ester, phenyl**. Use the terms **saturated** and **unsaturated**.	SL + HL
3.2.3 Homologous series	A homologous series is a family of compounds in which successive members differ by a common structural unit, typically CH_2. Each series can be described by a general formula.	Identify these homologous series: alkanes, alkenes, alkynes, halogenoalkanes, alcohols, aldehydes, ketones, carboxylic acids, ethers, amines, amides and esters.	SL + HL
3.2.4 Physical trends	Successive members of a homologous series show a trend in physical properties.	Describe and explain the trend in melting and boiling points of members of a homologous series.	SL + HL

Linking questions and connections for 3.2.1 – 3.2.4

- **Structure 2.2:** what is unique about carbon that enables it to form more compounds than all the other elements put together? → section 2.7
- **Nature of Science, Structure 2.2:** what are the advantages and disadvantages of the different depictions of an organic compound? **Tool 2:** how useful are 3D models for visualizing the invisible? → section 2.6
- HL **Structure 2.4:** what is the nature of the reaction that occurs when two amino acids form a dipeptide? → section 3.6
- **Nature of Science, Reactivity 3.2 and 3.4:** how can functional group reactivity be used to plan a reaction pathway between compounds, for example from ethene to ethanoic acid? → section 3.5
- **Structure 2.2:** what is the influence of chain length, branching and the nature of the functional group on intermolecular forces? → section 5

What the data booklet gives you — and what it does not

The data booklet has **no table of functional groups**. It does not give the names, structures or general formulas of the classes, the conventions for drawing skeletal formulas, or any boiling or melting points of organic compounds. All of these must be learned. It does give **enthalpies of combustion** (Section 14), which show a homologous series trend, **bond enthalpies** (Section 12), useful for explaining why carbon forms chains, and **electronegativities** (Section 9), which tell you which functional groups are polar. Later, at HL, Sections 20 to 22 (IR, ^{1}H NMR and mass spectra) are used to identify functional groups.

2 Structure 3.2.1 — Representing organic molecules SL + HL

2.1 Why one formula is not enough

Organic chemistry is the chemistry of carbon compounds. Almost all of them contain carbon–hydrogen bonds, and many also contain oxygen, nitrogen or a halogen. (A few simple carbon compounds, such as CO_2, CO and the carbonates, are traditionally treated as inorganic.) The problem with carbon compounds is that the same set of atoms can usually be joined together in several different ways, and each arrangement is a different compound with different properties. A formula that only counts the atoms cannot tell these compounds apart, so organic chemists use several kinds of formula, each showing a different level of detail.

2.2 Empirical and molecular formulas

Definitions to learn

- The **empirical formula** is the simplest whole-number ratio of the atoms of each element in a compound (Structure 1.4). Ethane, C_2H_6, has the empirical formula CH_3.
- The **molecular formula** is the actual number of atoms of each element in one molecule. It is a whole-number multiple, n, of the empirical formula: $\boldsymbol{M = n \times}$ **(molar mass of the empirical formula)**.

The empirical formula is what you get from the percentage composition, measured for example by combustion analysis. On its own it is of limited use: CH_2O is the empirical formula of methanal (CH_2O), ethanoic acid ($C_2H_4O_2$) and glucose ($C_6H_{12}O_6$). Knowing the molar mass converts it into the molecular formula. For many compounds the two are identical: methane, CH_4, and ethanol, C_2H_6O, cannot be simplified.

Worked example — from percentage composition to molecular formula

A compound contains 54.5% carbon, 9.1% hydrogen and 36.4% oxygen by mass. Its molar mass is 88 g mol^{-1}. Deduce its empirical and molecular formulas.

	C	H	O
mass in 100 g / g	54.5	9.1	36.4
amount / mol	54.5 ÷ 12.01 = 4.54	9.1 ÷ 1.01 = 9.0	36.4 ÷ 16.00 = 2.28
÷ smallest (2.28)	1.99 ≈ 2	3.96 ≈ 4	1

Empirical formula = **C_2H_4O**, molar mass = 2(12.01) + 4(1.01) + 16.00 = 44.06 g mol^{-1}. n = 88 ÷ 44.06 = 2, so the molecular formula is **$C_4H_8O_2$**.

But which compound is it? Butanoic acid, $CH_3CH_2CH_2COOH$, and ethyl ethanoate, $CH_3COOCH_2CH_3$, both have the formula $C_4H_8O_2$, yet one is an acid and the other a sweet-smelling ester. Only a **structural formula** can tell them apart.

2.3 Structural formulas: full and condensed

Definitions to learn

- A **structural formula** shows how the atoms are bonded to each other.
- A **full structural formula** (also called a displayed or graphic formula) shows **every atom and every bond**. Bonds are drawn at 90° and 180° because this is clearest on a flat page, but this is **not** the real shape of the molecule.
- A **condensed structural formula** leaves out bonds that can be assumed and groups atoms together, while still describing only **one** possible structure: $CH_3CH_2CH_2COOH$.

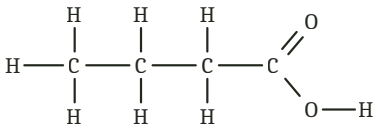
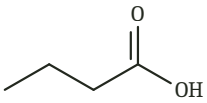
Type of formula	Butanoic acid	What it tells you
Empirical	C_2H_4O	the simplest ratio of atoms only
Molecular	$C_4H_8O_2$	the number of each kind of atom, but not how they are joined
Full structural		every atom and every bond; easiest to check, slowest to draw
Condensed structural	$CH_3CH_2CH_2COOH$	the order of the atoms and groups, in one line of text
Skeletal		the carbon skeleton and the functional group; quickest to draw

Figure 1 — Five formulas for the same molecule.

Conventions for condensed formulas

- Write each carbon followed by its hydrogens: $CH_3CH_2CH_2OH$.
- Put a **branch** in brackets straight after the carbon it is attached to: $CH_3CH(CH_3)CH_3$ is 2-methylpropane; $CH_3C(CH_3)_2CH_3$ has two methyl branches on the same carbon.
- Use the standard groupings for functional groups: –OH, **–CHO** (aldehyde, never –COH), –CO– (ketone), –COOH, –COO– (ester), $–CONH_2$, $–NH_2$, –O– (ether).
- Show a C=C double bond or a C≡C triple bond explicitly: $CH_2=CHCH_3$, $HC≡CCH_3$. It makes the formula unambiguous.

2.4 Stereochemical formulas

A **stereochemical formula** shows the three-dimensional arrangement of the atoms around a carbon atom. A plain line is a bond in the plane of the paper, a **solid wedge** is a bond coming **towards** you, and a **dashed (hashed) wedge** is a bond going **away** from you. The shapes are the ones predicted by VSEPR theory (Structure 2.2): four single bonds give a tetrahedral carbon, a double bond gives a trigonal planar carbon and a triple bond gives a linear one.

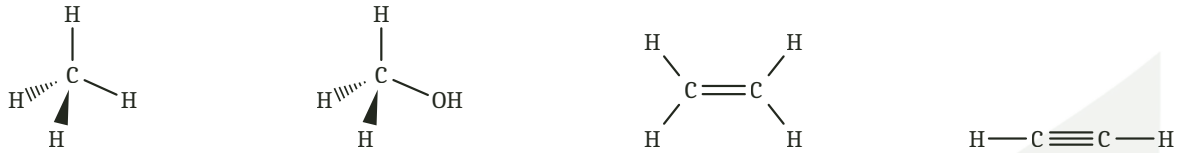


Figure 2 — Stereochemical formulas show the real geometry. Methane and methanol are tetrahedral; ethene is planar; ethyne is linear.

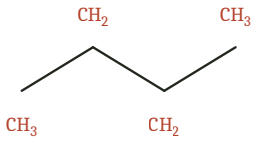
You must be able to **interpret** stereochemical formulas, but you will only be asked to **draw** them where a question specifically says so. They become essential at HL for stereoisomers (3.2.7).

2.5 Skeletal formulas

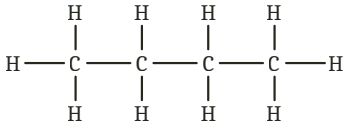
A **skeletal formula** is the shorthand that organic chemists use every day. It shows the carbon skeleton as a zig-zag of lines and leaves out most of the symbols.

The rules for reading and drawing skeletal formulas

- Every **end** of a line and every **bend** (corner) is a carbon atom. The symbol C is not written.
- Hydrogen atoms bonded to carbon are **not shown**. Every carbon makes four bonds, so the number of H atoms on a carbon = **4 − the number of bonds drawn to it** (a double bond counts as two).
- Atoms other than C and H are **always written**, together with any H attached to them: –OH, $–NH_2$, –CHO can be drawn as a line to O, and halogens are written as Cl, Br and so on.
- Double bonds are drawn as two lines and triple bonds as three. Chains are drawn as a zig-zag at about 120°, which is closer to the real shape than a straight line.
- A benzene ring, C_6H_6, is drawn as a hexagon with a circle inside. The rest of a molecule that does not matter for the question can be written as **R** (an alkyl group).



skeletal formula



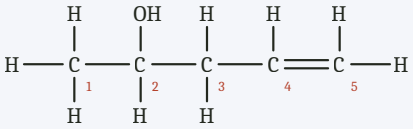
full structural formula

Figure 3 — Butane, C_4H_{10}. Each line end has one bond drawn, so it carries 3 H (CH_3); each bend has two bonds drawn, so it carries 2 H (CH_2).

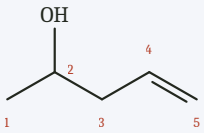
Compound	Condensed formula	Molecular formula	Skeletal formula
propan-2-ol	$CH_3CH(OH)CH_3$	C_3H_8O	
butanone	$CH_3COCH_2CH_3$	C_4H_8O	
2-methylpropane	$CH_3CH(CH_3)CH_3$	C_4H_{10}	
but-1-ene	$CH_2{=}CHCH_2CH_3$	C_4H_8	
propanal	CH_3CH_2CHO	C_3H_6O	
methyl ethanoate	CH_3COOCH_3	$C_3H_6O_2$	
methylbenzene	$C_6H_5CH_3$	C_7H_8	

Figure 4 — Condensed and skeletal formulas compared. You do not need to name these compounds yet (that is 3.2.5), but you must be able to convert between the formulas.

Worked example 1 — full structural formula → skeletal and condensed formulas

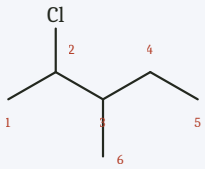


1. Number the carbon chain: there are five carbons in an unbranched chain, so the skeleton is a five-point zig-zag.
2. Carbon 2 carries an –OH group: draw a line up from point 2 and write OH at its end.
3. Carbons 4 and 5 are joined by a double bond: draw that bond as a double line.
4. Leave out every C and every H bonded to C.



Condensed: **$CH_3CH(OH)CH_2CH{=}CH_2$**. Molecular: **$C_5H_{10}O$**. (Check: 5 C; H = 3 + 1 + 2 + 1 + 2 + 1 on the O = 10.)

Worked example 2 — skeletal formula → condensed and molecular formulas



- Points 1 and 5 are line ends with one bond: CH_3.
- Point 2 has two C–C bonds and a C–Cl bond: 4 − 3 = **1 H**, so CHCl.
- Point 3 has three C–C bonds (including the branch, point 6): **1 H**, so CH.
- Point 4 has two bonds: CH_2. Point 6, the branch, is CH_3.

Condensed: **$CH_3CHClCH(CH_3)CH_2CH_3$**. Molecular: **$C_6H_{13}Cl$**.

Examiner traps in 3.2.1

- When a question asks for a **full** structural formula, every C, every H and every bond must be shown. Writing –OH or $-CH_3$ as a group in a full structural formula loses the mark: draw the O–H bond.
- Do not mix styles: a skeletal formula with some C or H labels on the carbon chain is wrong. Only H atoms on **O, N** (and other non-carbon atoms) are written.
- In a skeletal formula, check that the H count works: every carbon must end up with four bonds.
- Aldehydes are written –CHO, not –COH (–COH would mean an –OH on carbon).
- The empirical formula can be the same as the molecular formula. Do not divide C_2H_6O by anything.

2.6 Nature of Science — models and depictions

Every depiction of a molecule is a **model**: it shows some features and hides others. Choosing the right one is a skill in itself.

Depiction	Advantages	Disadvantages
Molecular formula	short; easy to calculate a molar mass	says nothing about structure; isomers look identical
Full structural	every bond visible; easy to count atoms and see functional groups	slow to draw for large molecules; 90° angles give a false impression of the shape
Condensed	fits in a line of text; unambiguous	hard to read for branched or ring compounds
Skeletal	very quick to draw; shows the carbon skeleton and functional groups clearly; zig-zag close to the real shape	H atoms must be worked out; easy to miscount carbons
Stereochemical	shows the 3D arrangement around a carbon	awkward to draw; only practical near one or two atoms
3D models (kits or software)	show true bond angles and shape; can be rotated	not to scale (see below); ball-and-stick hides the size of atoms; space-filling hides the bonds



ball-and-stick *space-filling*

Figure 5 — Two 3D models of methane. Ball-and-stick shows the bonds and the tetrahedral angles; space-filling shows the relative sizes of the atoms and the overall shape that other molecules 'see'.

Nature of Science and TOK — visualizing the invisible (Tool 2)

A C–C bond is 154 pm long and a carbon nucleus has a radius of about 2.7×10^{-15} m. In a kit where the nucleus is a ball of radius 0.5 cm, the stick for one C–C bond would need to be $(154 \times 10^{-12} \div 2.7 \times 10^{-15}) \times 0.5$ cm $\approx 2.9 \times 10^{4}$ cm, that is, nearly **300 m** long. No model is to scale. Models are useful because they are simplified, but every model carries hidden assumptions. TOK: how do we decide whether a model is 'good' when the thing it represents cannot be seen?

2.7 Why carbon forms so many compounds

Carbon is unusual in its ability to form stable chains of its own atoms, a property called **catenation**. Three features work together:

- Carbon has **four valence electrons**, so each carbon atom forms **four covalent bonds**. This allows long chains, branches and rings.
- The **C–C bond is strong** (346 kJ mol^{-1}, data booklet Section 12), much stronger than Si–Si (226 kJ mol^{-1}), so carbon chains are stable. C–H, C–O and C–N bonds are also strong.
- Carbon forms **single, double and triple bonds**, to itself and to other atoms such as O and N.

HL **Hybridization and the shapes of carbon (Structure 2.2)**

The different bond types come from the different ways carbon hybridizes its 2s and 2p orbitals:

Hybridization	Bonds formed	Shape and angle	Example
sp^3	four σ bonds	tetrahedral, 109.5°	every carbon in an alkane
sp^2	three σ bonds + one π bond (a C=C or C=O)	trigonal planar, 120°	the C=C carbons in ethene; the carbonyl carbon
sp	two σ bonds + two π bonds (a C≡C)	linear, 180°	the C≡C carbons in ethyne

Because carbon can use all three, a single molecule can contain tetrahedral, planar and linear carbons, which adds further to the variety of possible structures.

Model answer: "Explain why carbon is able to form a very large number of compounds." (3 marks)

Carbon has four valence electrons and forms four covalent bonds **[1]**. C–C bonds are strong, so carbon atoms can bond to each other in stable chains, branches and rings (catenation) **[1]**. Carbon can also form single, double and triple bonds, to itself and to other elements such as O, N and the halogens **[1]**.

3 Structure 3.2.2 — Functional groups and classes of compound SL + HL

3.1 Functional groups and classes

Definitions to learn

- A **functional group** is an atom or group of atoms in an organic molecule that is responsible for its characteristic physical properties and chemical reactions.
- A **class** of compounds is the set of compounds that contain the same functional group, for example the carboxylic acids, which all contain –COOH.
- A **hydrocarbon** contains carbon and hydrogen only. An **alkyl group** is an alkane minus one hydrogen atom, for example $–CH_3$ (methyl) or $–C_2H_5$ (ethyl). It is often written **R**; if there are two, possibly different, alkyl groups they are written R and R′.

The carbon skeleton of most organic molecules is fairly unreactive: C–C and C–H bonds are strong and almost non-polar. The chemistry happens at the functional group, where there are polar bonds, lone pairs or π bonds. That is why compounds in the same class react in the same way, however long their carbon chains.

3.2 Saturated and unsaturated

Definitions to learn

- A **saturated** compound contains only **single** carbon–carbon bonds. Alkanes are saturated.
- An **unsaturated** compound contains at least one carbon–carbon **double or triple** bond. Alkenes and alkynes are unsaturated.

The words come from the idea that a saturated compound holds the maximum possible number of hydrogen atoms for its carbon skeleton. Unsaturated compounds can take up more atoms by **addition** across the multiple bond, while saturated ones re-

act mainly by **substitution** (Reactivity 3.3 and 3.4). The terms are also used for fats: unsaturated fats contain C=C bonds in their long hydrocarbon chains, and health agencies recommend them in preference to saturated fats.

3.3 The nine functional groups you must recognize

The guide lists nine functional groups that you must identify **by name and by structure**. Notice that the name of the **group** (hydroxyl) is not the same as the name of the **class** (alcohols).

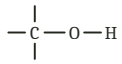
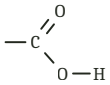
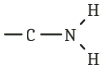
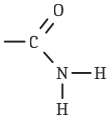
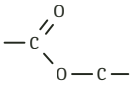
Functional group	Structure	Found in (class)	Example
halogeno	 –X (X = F, Cl, Br, I)	halogenoalkanes	CH_3CH_2Cl, chloroethane
hydroxyl	 –OH	alcohols	CH_3CH_2OH, ethanol
carbonyl	 –CHO and –CO–	aldehydes (C=O at the end of the chain) ketones (C=O within the chain)	CH_3CHO, ethanal CH_3COCH_3, propanone
carboxyl	 –COOH	carboxylic acids	CH_3COOH, ethanoic acid
alkoxy	–O–R	ethers	$CH_3OCH_2CH_3$, methoxyethane
amino	 –NH_2	amines	$CH_3CH_2NH_2$, ethanamine
amido	 –$CONH_2$	amides	CH_3CONH_2, ethanamide
ester	 –COO–	esters	CH_3COOCH_3, methyl ethanoate
phenyl	 –C_6H_5	aromatic compounds (a benzene ring with one H replaced)	$C_6H_5CH_3$, methylbenzene

Figure 6 — The functional groups named in the guide. The C=C (alkenes) and C≡C (alkynes) are also functional groups and are needed for 3.2.3, but they are not in this list of names.

Phenyl: recognize it, do not classify it

When a benzene ring is attached to the rest of a molecule by one bond, the ring is a **phenyl** group, $-C_6H_5$. You must recognize it in any structure, but arenes are not required as a class, and you do not need to name compounds that contain a phenyl group. Methylbenzene (traditionally *toluene*) is a methyl group joined to a phenyl group.

3.4 Telling similar functional groups apart

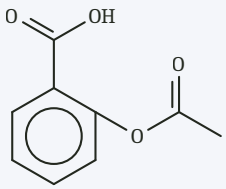
Many functional groups contain oxygen, and several contain a C=O, so the commonest errors come from looking at only part of the group. Use this method:

Method — identify an oxygen- or nitrogen-containing group

1. **Is there a C=O?** If not: an O joined to H is **hydroxyl** (alcohol); an O between two carbons is **alkoxy** (ether); an N carrying H atoms is **amino** (amine).
2. **If there is a C=O, look at what else is joined to that same carbon:** an H → aldehyde (carbonyl); two carbons → ketone (carbonyl); an –OH → **carboxyl**; an –O–C → **ester**; an N → **amido**.

Look-alike pair	Formula	Group and class	The difference
CH_3CH_2OH CH_3OCH_3	both C_2H_6O	hydroxyl, alcohol alkoxy, ether	O–H present, or O between two C
CH_3CH_2CHO CH_3COCH_3	both C_3H_6O	carbonyl, aldehyde carbonyl, ketone	C=O at the end (with H), or inside the chain
CH_3CH_2COOH CH_3COOCH_3	both $C_3H_6O_2$	carboxyl, carboxylic acid ester, ester	C(=O)–O–H, or C(=O)–O–C
$CH_3CH_2NH_2$ CH_3CONH_2	C_2H_7N C_2H_5NO	amino, amine amido, amide	N on a CH_2, or N on a C=O
CH_3COCH_2OH CH_3CH_2COOH	both $C_3H_6O_2$	carbonyl + hydroxyl carboxyl	–COOH only when C=O and O–H are on the **same** carbon

Worked example — identify the functional groups in aspirin



- The six-membered ring with a circle, joined to the rest of the molecule, is a **phenyl** group.
- At the top, a C=O and an O–H on the same carbon: a **carboxyl** group.
- On the right, a C=O whose carbon is also joined to an O that is bonded to the ring: an **ester** group. (It is not an ether: the O is next to a C=O.)

3.5 Functional groups decide the chemistry: reaction pathways

Because each functional group has its own reactions, a chemist can plan a **reaction pathway**: a sequence of steps in which the product of one reaction is the starting material of the next, each step converting one functional group into another. Ethanoic acid, for example, can be made from ethene in two steps (the reactions themselves are covered in Reactivity 3.2 and 3.4):

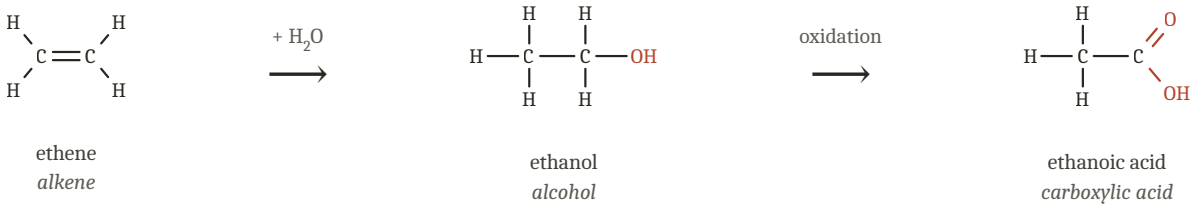


Figure 7 — A two-step pathway: C=C → hydroxyl → carboxyl. The functional group changes at each step; the C–C skeleton does not.

3.6 Amino acids join by condensation HL

Amino acids contain **two** functional groups: an **amino** group, $-NH_2$, and a **carboxyl** group, –COOH, on the same carbon. The carboxyl group of one amino acid can react with the amino group of another in a **condensation reaction**: the two molecules join and a small molecule, **water**, is eliminated.

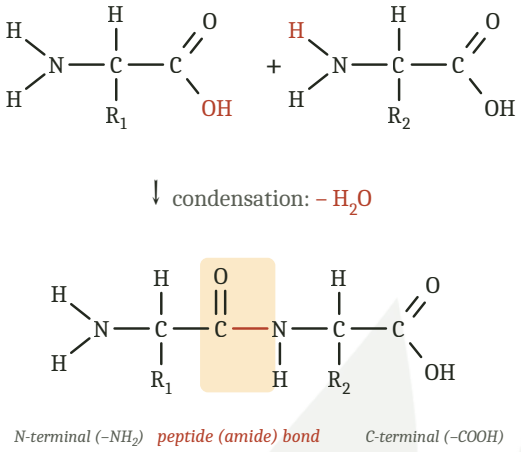


Figure 8 — Two amino acids (R_1 and R_2 are side chains) condense to form a dipeptide. The new –CONH– link (shaded) is an amide link, called a **peptide bond**.

The dipeptide still has a free $-NH_2$ at one end and a free –COOH at the other, so it can condense again to give a tripeptide, and so on to a **polypeptide**. Proteins such as haemoglobin are built from long polypeptide chains. Two different amino acids can join in two orders (AB or BA), giving two different dipeptides. Condensation polymers are developed further in Structure 2.4 and Reactivity 3.4.

Model answer: "Describe how two amino acids react to form a dipeptide." (3 marks)

A condensation reaction occurs between the carboxyl group of one amino acid and the amino group of the other **[1]**. A molecule of water is eliminated **[1]**. The two are joined by an amide link (peptide bond), –CONH– **[1]**.

Model answer: "State the names of the functional groups present in $HOCH_2CH_2COOCH_3$." (2 marks)

Hydroxyl (–OH) **[1]**; ester (–COO–) **[1]**. (Do not give 'carbonyl' or 'carboxyl': the C=O is part of the ester group, and there is no O–H on the C=O carbon.)

Examiner traps in 3.2.2

- Learn the group names **and** the class names: **hydroxyl** group / alcohol; **carboxyl** group / carboxylic acid; **amino** group / amine; **amido** group / amide; **alkoxy** group / ether. Answer with the one the question asks for.
- **Hydroxyl**, never 'hydroxide': –OH in an alcohol is covalently bonded and is not an OH^- ion.
- **Carbonyl** (C=O, in aldehydes and ketones) and **carboxyl** (–COOH) are different groups. Spell them carefully.
- **Ether** (C–O–C) and **ester** (C(=O)–O–C) differ by one letter and one C=O.
- **Amine** (–NH_2 on an alkyl carbon) and **amide** (–NH_2 on a C=O carbon) are not interchangeable.
- **Phenyl** is the group –C_6H_5; benzene is the compound C_6H_6.
- Saturated / unsaturated refers to carbon–carbon bonds: say 'contains only single C–C bonds' or 'contains a C=C or C≡C bond'.

4 Structure 3.2.3 — Homologous series SL + HL

4.1 What makes a homologous series

Definition to learn

A **homologous series** is a family of compounds with the same functional group, in which successive members differ by a common structural unit, usually **–CH_2–**. Each series can be described by a **general formula**.

Characteristics of the members of a homologous series:

- they have the **same functional group** and the **same general formula**;
- successive members differ by **CH_2**, so their molar masses differ by 14 g mol^{-1};
- they have **similar chemical properties**, because they have the same functional group;
- they show a **gradual trend in physical properties** (boiling point, melting point, density, viscosity) as the chain gets longer.

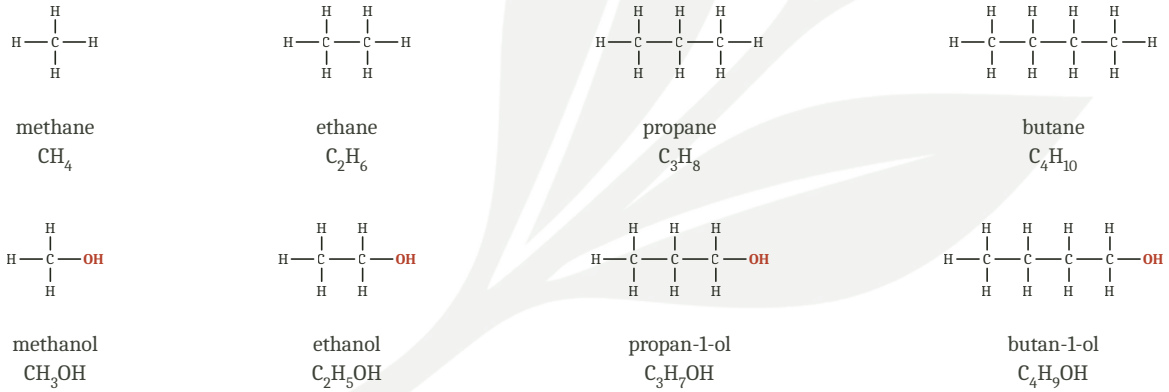


Figure 9 — The first four alkanes, C_nH_{2n+2}, and the first four alcohols, $C_nH_{2n+1}OH$. Each member has one more –CH_2– than the one before. The alcohols all carry the same –OH group (red).

4.2 The twelve series and their general formulas

Homologous series	Functional group	General formula	First member	Second member
alkanes	none (C–C, C–H only)	C_nH_{2n+2}	CH_4 methane	C_2H_6 ethane
alkenes	C=C	C_nH_{2n}	C_2H_4 ethene	C_3H_6 propene
alkynes	C≡C	C_nH_{2n-2}	C_2H_2 ethyne	C_3H_4 propyne
halogenoalkanes	–X (halogeno)	$C_nH_{2n+1}X$	CH_3Cl chloromethane	C_2H_5Cl chloroethane
alcohols	–OH (hydroxyl)	$C_nH_{2n+1}OH$	CH_3OH methanol	C_2H_5OH ethanol
ethers	–O– (alkoxy)	$C_nH_{2n+2}O$ R–O–R′	CH_3OCH_3 methoxymethane	$CH_3OC_2H_5$ methoxyethane
aldehydes	–CHO (carbonyl)	$C_nH_{2n}O$ R–CHO	HCHO methanal	CH_3CHO ethanal
ketones	–CO– (carbonyl)	$C_nH_{2n}O$ R–CO–R′	CH_3COCH_3 propanone	$CH_3COC_2H_5$ butanone
carboxylic acids	–COOH (carboxyl)	$C_nH_{2n+1}COOH$ or $C_nH_{2n}O_2$	HCOOH methanoic acid	CH_3COOH ethanoic acid
esters	–COO– (ester)	$C_nH_{2n}O_2$ R–COO–R′	$HCOOCH_3$ methyl methanoate	CH_3COOCH_3 methyl ethanoate
amines	$–NH_2$ (amino)	$C_nH_{2n+1}NH_2$	CH_3NH_2 methanamine	$C_2H_5NH_2$ ethanamine
amides	$–CONH_2$ (amido)	$C_nH_{2n+1}CONH_2$	$HCONH_2$ methanamide	CH_3CONH_2 ethanamide

Figure 10 — General formulas. In $C_nH_{2n+1}COOH$ and $C_nH_{2n+1}CONH_2$, n counts the carbons in the alkyl group only, so the first member has $n = 0$ (HCOOH, $HCONH_2$). Notice that the first member is not always a one-carbon compound: a ketone needs at least three carbons, an alkene, alkyne, ether or ester at least two.

One general formula, two series

Several pairs of series share a general formula: $C_nH_{2n}O$ (aldehydes and ketones), $C_nH_{2n}O_2$ (carboxylic acids and esters) and $C_nH_{2n+2}O$ (alcohols and ethers). Alkenes also share C_nH_{2n} with the ring compounds called cycloalkanes. So a molecular formula alone such as C_3H_6O does not tell you the class; the compounds are **structural isomers** (3.2.6), and you need the structural formula to decide.

Worked examples — using general formulas

(a) Identify the possible series for C_4H_{10}, C_4H_8 and $C_4H_8O_2$. C_4H_{10} fits C_nH_{2n+2} with $n = 4$: an **alkane**. C_4H_8 fits C_nH_{2n}: an **alkene** (or a cycloalkane). $C_4H_8O_2$ fits $C_nH_{2n}O_2$: a **carboxylic acid or an ester**.

(b) A carboxylic acid has a molar mass of 74 g mol^{-1}. Deduce its formula. For $C_nH_{2n+1}COOH$, $M = 12n + (2n + 1) + 12 + 32 + 1 = 14n + 46$ (using whole-number masses). $14n + 46 = 74$, so $n = 2$: the acid is $\mathbf{C_2H_5COOH}$, propanoic acid.

(c) State the molecular formula of the alcohol with six carbon atoms. $C_nH_{2n+1}OH$ with $n = 6$: $\mathbf{C_6H_{13}OH}$ (or $C_6H_{14}O$).

4.3 Similar chemical properties, gradually changing

Because every member has the same functional group, the members of a series undergo the same reactions, and you can write a general equation for the whole series. All alkanes and all alcohols burn completely in excess oxygen to give carbon dioxide and water, for example. The quantities change regularly: each extra $–CH_2–$ adds about the same amount of energy released on combustion.

Alcohol	CH_3OH	C_2H_5OH	C_3H_7OH	C_4H_9OH
$\Delta H_c^{\ominus}$ / kJ mol^{-1}	−726	−1367	−2021	−2676
difference / kJ mol^{-1}		−641	−654	−655

Figure 11 — Enthalpies of combustion of the first four alcohols (data booklet, Section 14). Each extra CH_2 adds roughly 650 kJ mol^{-1}. The alkanes show the same pattern (−891, −1561, −2219, −2878 kJ mol^{-1}).

Examiner traps in 3.2.3

- A definition of a homologous series needs **both** ideas: the same functional group (same general formula) **and** successive members differing by CH_2.
- Members of a series have **similar** chemical properties but **different** physical properties that change gradually. Do not say they have the 'same properties'.
- Two compounds with the same molecular formula are **not** in the same series (they differ by nothing, not by CH_2); they are isomers, which may well belong to different series.
- Check general formulas by counting: C_3H_7OH has 8 H in total, but the general formula is written $C_nH_{2n+1}OH$ so that the –OH stays visible.
- Methanal is HCHO and methanoic acid is HCOOH: the first aldehyde and the first acid have an H, not an alkyl group, on the functional group carbon.

5 Structure 3.2.4 — Trends in physical properties

SL + HL

5.1 Boiling point rises with chain length

When a molecular substance boils, the molecules are separated from each other: the **intermolecular forces** are overcome, but **no covalent bonds are broken**. So the boiling point is a measure of how strong the intermolecular forces are (Structure 2.2).

C atoms	Alkane	b.p. / °C	1-Chloroalkane	b.p. / °C	Alcohol	b.p. / °C
1	methane	−164	chloromethane	−24	methanol	65
2	ethane	−89	chloroethane	12	ethanol	78
3	propane	−42	1-chloropropane	46	propan-1-ol	97
4	butane	−0.5	1-chlorobutane	78	butan-1-ol	118
5	pentane	36	1-chloropentane	108	pentan-1-ol	138
6	hexane	69	1-chlorohexane	135	hexan-1-ol	156
7	heptane	98	1-chloroheptane	159	heptan-1-ol	176
8	octane	125	1-chlorooctane	182	octan-1-ol	194

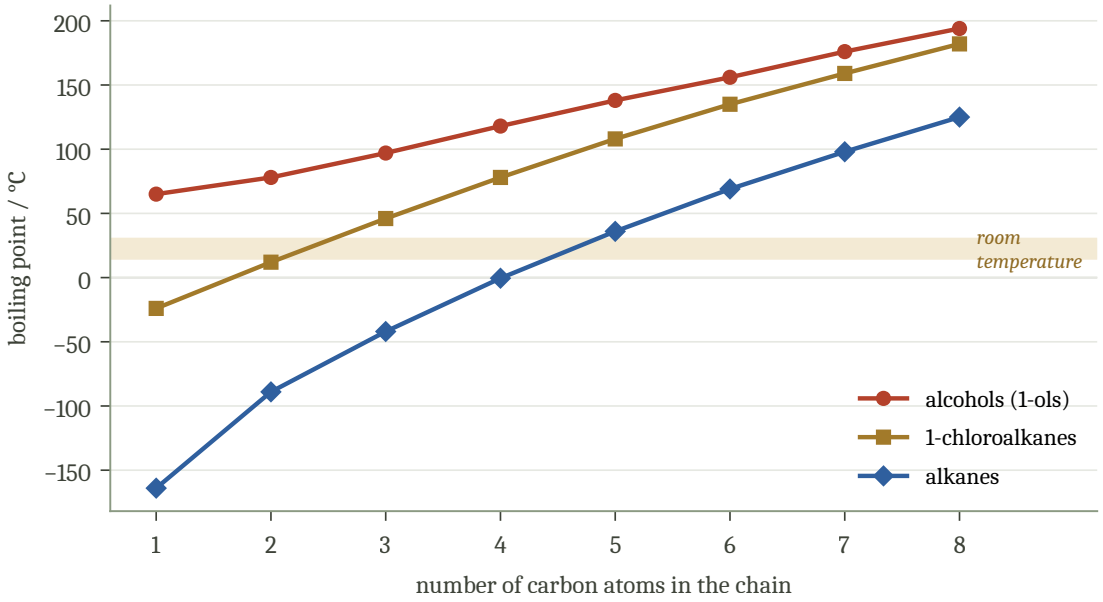


Figure 12 — Boiling points of the first eight members of three homologous series. Within each series the boiling point rises steadily with chain length. The shaded band is room temperature: the first four alkanes are gases, while even methanol is a liquid.

The explanation — chain length and London dispersion forces

- Each additional –CH_2– adds **8 more electrons** and makes the molecule longer, with a larger **surface area** of contact with its neighbours.
- More electrons means the electron cloud is more easily distorted (more polarizable), so larger **instantaneous and induced dipoles** form.
- So the **London dispersion forces** between molecules become **stronger**, more energy is needed to separate the molecules, and the boiling point is **higher**.

The same reasoning explains why the members of a series also become more **viscous** and less **volatile** as the chain gets longer. **Volatility** is the tendency of a substance to vaporize: a substance with weak intermolecular forces has a low boiling point and is highly volatile.

5.2 Why the increase gets smaller

For the alkanes, the rise from one member to the next is large at first and then shrinks: methane → ethane is +75 °C, but heptane → octane only +27 °C. Adding one CH_2 to methane almost doubles the number of electrons (10 → 18), but adding one CH_2 to heptane increases it by only about 14% (58 → 66). The **proportional** increase in the dispersion forces is therefore much smaller for longer chains. For the chloroalkanes and alcohols the rise is more even, because in the small molecules the forces due to the functional group (dipole–dipole forces, hydrogen bonds) dominate, and the chain adds a steady extra amount.

5.3 Melting points

Melting points also rise along a series, but **less regularly** than boiling points. To melt, molecules only have to break free of their fixed positions in the solid lattice, and how much energy that needs depends not only on the strength of the dispersion forces but also on **how well the molecules pack** together. Small differences in shape change the packing, so the melting points zig-zag a little. For the short alkanes, the melting point of propane is even lower than that of ethane; further up the series, alkanes with an even number of carbons pack slightly better and have relatively higher melting points.

C	Alkane	m.p. / °C	b.p. / °C
1	methane	−182	−164
2	ethane	−183	−89
3	propane	−188	−42
4	butane	−138	−0.5
5	pentane	−130	36
6	hexane	−95	69
7	heptane	−91	98
8	octane	−57	125

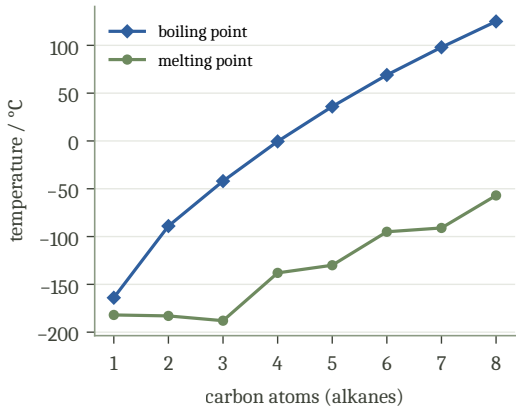


Figure 13 — Melting and boiling points of the first eight alkanes. Both rise overall, but the melting points do so unevenly. Alkanes with up to four carbons are gases at room temperature, those from about C_5 to C_{16} are liquids, and longer ones are waxy solids (paraffin wax).

5.4 The functional group matters even more

Look across any row of the table in section 5.1: with the same number of carbons, the boiling points increase in the order alkane < chloroalkane < alcohol. A fairer test compares molecules with about the **same number of electrons** (similar molar mass), so that the London dispersion forces are similar and only the functional group changes:

Compound	M / g mol^{-1}	Strongest intermolecular force	b.p. / °C
propane, $CH_3CH_2CH_3$	44	London dispersion forces only (non-polar)	−42
methoxymethane, CH_3OCH_3	46	dipole–dipole (polar C–O bonds; no O–H)	−24
ethanal, CH_3CHO	44	dipole–dipole (very polar C=O)	20
ethanol, CH_3CH_2OH	46	hydrogen bonding (O–H)	78
methanoic acid, HCOOH	46	hydrogen bonding (O–H and C=O; forms dimers)	101

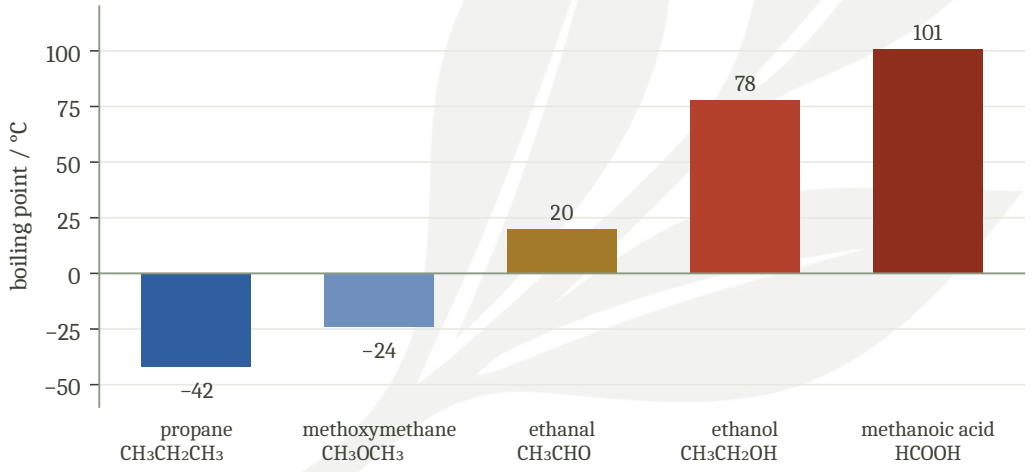


Figure 14 — Five compounds of almost the same molar mass. The boiling point depends on the functional group: the stronger the intermolecular forces it allows, the higher the boiling point.

most volatile (lowest b.p.) **least volatile (highest b.p.)**

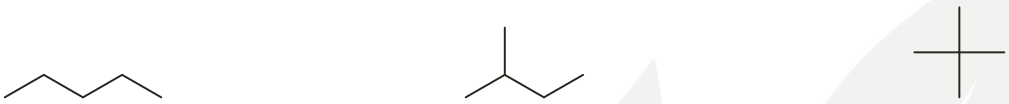
alkane > halogenoalkane > aldehyde > ketone > alcohol > carboxylic acid

London dispersion only → dipole–dipole forces → hydrogen bonding · increasing strength of intermolecular forces →

Figure 15 — Volatility for compounds of similar size. Use this order only when chain length and molar mass are comparable: a long-chain alkane such as octane (125 °C) boils far higher than methanol (65 °C).

- **Alkanes** are non-polar: London dispersion forces only.
- **Halogenoalkanes, aldehydes, ketones, ethers and esters** are polar (C–X, C=O, C–O bonds) and have permanent dipole–dipole forces in addition, but none of them has an H on O or N, so there is **no hydrogen bonding between their molecules**. Ketones boil slightly higher than the isomeric aldehydes (propanone 56 °C, propanal 48 °C).
- **Alcohols, carboxylic acids, amines and amides** have O–H or N–H bonds and form **hydrogen bonds**. Carboxylic acids have both a C=O and an O–H, form two hydrogen bonds per pair of molecules (dimers) and have the highest boiling points. Amines form weaker hydrogen bonds than alcohols, because N (3.0) is less electronegative than O (3.4): ethanamine boils at 17 °C, ethanol at 78 °C. Amides form several hydrogen bonds per molecule: ethanamide is a solid at room temperature.
- Isomers show the effect most clearly: propanoic acid (CH_3CH_2COOH, 141 °C) and methyl ethanoate (CH_3COOCH_3, 57 °C) have the same formula, $C_3H_6O_2$, but only the acid can hydrogen bond.

5.5 Branching lowers the boiling point



pentane
b.p. 36 °C

2-methylbutane
b.p. 28 °C

2,2-dimethylpropane
b.p. 10 °C

Figure 16 — Three isomers of C_5H_{12}. Same number of electrons, but the more branched the molecule, the lower the boiling point.

Branched molecules are more compact and closer to spherical. They cannot line up alongside each other as closely as straight chains, so the **surface area of contact** between neighbouring molecules is smaller, the London dispersion forces are weaker and less energy is needed to separate them. You will meet these compounds again as structural isomers (3.2.6).

5.6 Solubility in water

The small alcohols and carboxylic acids mix completely with water, because their –OH groups form hydrogen bonds with water molecules. As the chain gets longer, the non-polar hydrocarbon part makes up more of the molecule; it cannot hydrogen bond with water and it disrupts the hydrogen bonding between water molecules. Solubility in water therefore **decreases** along a series: methanol, ethanol and propan-1-ol are fully miscible, butan-1-ol is only partly soluble and hexan-1-ol barely dissolves. Alkanes, with no polar group at all, are insoluble.

Global impact — fractional distillation of crude oil

Crude oil is a mixture of many alkanes and other hydrocarbons. Because boiling point rises predictably with chain length, the mixture can be separated by **fractional distillation**. Small molecules (refinery gas, petrol) rise to the top of the column, while long-chain molecules (diesel, lubricating oil, bitumen) condense lower down. Each fraction contains molecules with a similar number of carbon atoms and a similar boiling range, and each has its own uses as a fuel or as a feedstock for the chemical industry.

Model answer: "Describe and explain the trend in boiling points of the first five members of the alkane homologous series." (3 marks)

The boiling point increases as the number of carbon atoms increases **[1]**. Each member has one more CH_2, so more electrons and a larger surface area, giving stronger London dispersion forces between the molecules **[1]**. More energy is needed to overcome these intermolecular forces and separate the molecules **[1]**.

Model answer: "Ethanol, C_2H_5OH, boils at 78 °C, but methoxymethane, CH_3OCH_3, boils at −24 °C. Explain the difference." (3 marks)

Both have similar molar masses (46 g mol^{-1}), so similar London dispersion forces **[1]**. Ethanol has an O–H group, so hydrogen bonds form between its molecules **[1]**. Methoxymethane has no H bonded to O, so it has only (weaker) dipole–dipole and London dispersion forces; less energy is needed to separate its molecules **[1]**.

Model answer: "Explain why 2,2-dimethylpropane has a lower boiling point than pentane." (2 marks)

2,2-Dimethylpropane is more branched/more spherical, so there is a smaller surface area of contact between its molecules **[1]**. The London dispersion forces are weaker, so less energy is needed to separate the molecules (both have the same number of electrons) **[1]**.

Examiner traps in 3.2.4

- Boiling separates molecules: **intermolecular forces** are overcome. Writing that 'C–C bonds break' or 'covalent bonds break' scores zero.
- Explain the chain-length trend with **London dispersion forces** and the **number of electrons / surface area**. 'Heavier molecules' or 'more mass' alone is not accepted as the reason.
- Hydrogen bonds form **between** molecules of an alcohol (O–H…O), not within one molecule. An H on carbon cannot hydrogen bond.
- When comparing functional groups, compare molecules of similar molar mass, and name the strongest force for each compound.
- 'Describe' needs the trend (it increases); 'explain' needs the reason (stronger dispersion forces, more energy to separate the molecules). Many questions ask for both.
- Esters, ethers, aldehydes and ketones contain oxygen but do **not** hydrogen bond with each other.

6 Key points to memorise

Everything below is either wording that examiners look for, or knowledge you must carry into the exam yourself.

A Definitions — near-verbatim

- **Empirical formula:** simplest whole-number ratio of atoms. **Molecular formula:** actual number of atoms of each element in a molecule; $M = n \times M$(empirical formula).
- **Full structural formula:** every atom and every bond shown. **Condensed:** atoms grouped, bonds omitted, still unambiguous. **Skeletal:** C and H on C not shown; line ends and bends are carbons.
- **Stereochemical formula:** 3D arrangement; wedge = towards you, dash = away.
- **Functional group:** atom or group of atoms responsible for a compound's characteristic properties and reactions. **Class:** compounds with the same functional group.
- **Saturated:** only single C–C bonds. **Unsaturated:** contains a C=C or C≡C.
- **Homologous series:** same functional group and general formula; successive members differ by CH_2; similar chemical properties; gradual trend in physical properties.

B The nine functional groups (name → structure → class)

- **halogeno** –X → halogenoalkanes · **hydroxyl** –OH → alcohols · **carbonyl** C=O → aldehydes (–CHO) and ketones (–CO–)
- **carboxyl** –COOH → carboxylic acids · **alkoxy** –OR → ethers · **amino** $-NH_2$ → amines
- **amido** $-CONH_2$ → amides · **ester** –COO– → esters · **phenyl** $-C_6H_5$ (recognize only)

C General formulas

- alkanes C_nH_{2n+2} · alkenes C_nH_{2n} · alkynes C_nH_{2n-2} · halogenoalkanes $C_nH_{2n+1}X$ · alcohols $C_nH_{2n+1}OH$
- aldehydes and ketones $C_nH_{2n}O$ · carboxylic acids $C_nH_{2n+1}COOH$ ($C_nH_{2n}O_2$) · esters $C_nH_{2n}O_2$ · ethers $C_nH_{2n+2}O$ · amines $C_nH_{2n+1}NH_2$ · amides $C_nH_{2n+1}CONH_2$
- Shared general formulas mean structural isomers in different classes.

D Physical trends

- Longer chain → more electrons, larger surface area → stronger London dispersion forces → higher b.p. and m.p., lower volatility, higher viscosity.
- The increase per CH_2 gets smaller as the chain grows (smaller proportional change). Melting points rise less regularly (packing).
- Similar M: alkane < halogenoalkane, aldehyde, ketone, ether, ester (dipole–dipole) < alcohol < carboxylic acid (hydrogen bonding).
- Branching → more spherical → less contact → weaker dispersion forces → lower b.p. Longer chain → less soluble in water.
- HL sp^3 tetrahedral 109.5°; sp^2 trigonal planar 120°; sp linear 180°. Amino acids condense ($-H_2O$) to form a peptide (amide) bond, –CONH–.

E Command terms — what each one is actually asking for

- **Identify** (a functional group) — name it; no explanation needed. Give the group name if asked for the group, the class name if asked for the class.
- **Deduce** (a molecular or condensed formula) — work it out from the information given, showing the H count or the general formula.
- **Draw** (a full structural formula) — every atom and bond, clearly. A skeletal formula is only accepted where the question allows it.
- **Describe** (a trend) — say what happens: 'boiling point increases as the chain length increases'.
- **Explain** (a trend or a difference) — give the cause: the type of intermolecular force, why it is stronger, and that more energy is needed to separate the molecules.

7 Check yourself

Cover the answers on the next pages. Marks are shown in brackets where a question is written in exam style. Questions marked HL are for Higher Level students.

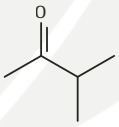
1. Which compound has the same empirical formula as ethanoic acid, CH_3COOH?

   A glucose, $C_6H_{12}O_6$ B ethanol, C_2H_5OH
   C methanol, CH_3OH D propanoic acid, C_2H_5COOH

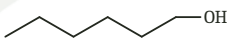
2. A compound contains 40.0% C, 6.7% H and 53.3% O by mass. Its molar mass is 60 g mol^{-1}. Deduce its empirical and molecular formulas. **[3]**

3. Draw (a) the full structural formula and (b) the skeletal formula of $CH_3CH(CH_3)CH_2OH$. **[2]**

4. Deduce the condensed structural formula and the molecular formula of the compound shown. **[2]**



5. What is the molecular formula of the compound shown?



   A $C_6H_{13}O$ B $C_6H_{14}O$ C $C_6H_{12}O$ D $C_5H_{12}O$

6. State **one** advantage and **one** disadvantage of a skeletal formula compared with a full structural formula. **[2]**

7. Outline **two** reasons why carbon forms such a large number of compounds. **[2]**

8. Which functional group is present in $CH_3CH_2CONH_2$?

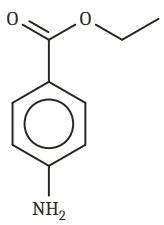
   A amino B amido C carboxyl D ester

9. Which compound is unsaturated?

   A $CH_3CH_2CH_3$ B CH_3CH_2Cl C $CH_3C{\equiv}CH$ D $(CH_3)_3COH$

10. Identify the functional group, by name, and the class of compound for: (a) CH_3CH_2CHO (b) $CH_3COCH_2CH_3$ (c) $CH_3CH_2COOCH_3$ (d) $CH_3OCH_2CH_3$ (e) $CH_3CH_2CH_2NH_2$ (f) $CH_3CH_2CH_2Br$. **[6]**

11. Benzocaine is used as a local anaesthetic. Identify the **three** functional groups in its structure. **[3]**



12. CH_3CH_2COOH and CH_3COOCH_3 have the same molecular formula. Explain why they belong to different classes of compound. **[2]**

13. Define the term *homologous series* and state **two** characteristics of its members. **[3]**

14. Which is the general formula of the ketones?

A $C_nH_{2n+2}O$ B $C_nH_{2n}O$ C $C_nH_{2n}O_2$ D $C_nH_{2n+1}OH$

15. Which compound is in the same homologous series as $CH_3CH_2CH_2COOH$?

A CH_3COOCH_3 B CH_3COOH C CH_3CH_2CHO D $CH_3CH_2OCH_3$

16. Which molecular formulas could each represent compounds from two different homologous series? I. C_3H_6O II. C_3H_8O III. $C_3H_6O_2$

A I and II only B I and III only C II and III only D I, II and III

17. An alcohol in the series $C_nH_{2n+1}OH$ has a molar mass of 88 g mol^{-1}. Deduce its molecular formula and state the formula of the next member of the series. **[2]**

18. Describe and explain the trend in the boiling points of the alcohols from methanol to butan-1-ol. **[3]**

19. Which shows the compounds in order of increasing boiling point?

A $CH_3CH_2CH_3 < CH_3CHO < CH_3CH_2OH$ B $CH_3CHO < CH_3CH_2CH_3 < CH_3CH_2OH$
C $CH_3CH_2OH < CH_3CHO < CH_3CH_2CH_3$ D $CH_3CH_2CH_3 < CH_3CH_2OH < CH_3CHO$

20. Propanoic acid boils at 141 °C, but its isomer methyl ethanoate boils at 57 °C. Explain the difference. **[3]**

21. Explain why the boiling point of 2-methylbutane is lower than that of pentane. **[2]**

22. Explain why the difference in boiling point between successive alkanes becomes smaller as the chain gets longer. **[2]**

23. Suggest why the melting points of the alkanes do not increase as regularly as their boiling points. **[1]**

24. List butane, propanal and propan-1-ol (all $M \approx 58$–60 g mol^{-1}) in order of increasing boiling point, and explain your order. **[3]**

25. Suggest why the solubility of the alcohols in water decreases from methanol to hexan-1-ol. **[2]**

26. HL State the hybridization of each carbon atom in propene, $CH_2{=}CHCH_3$, and in propyne, $HC{\equiv}CCH_3$. **[2]**

27. HL Glycine is H_2NCH_2COOH and alanine is $H_2NCH(CH_3)COOH$. Draw the structure of **one** dipeptide that they can form, name the bond formed and the other product. **[3]**

28. HL Explain why amino acids can join together to form long polypeptide chains. **[2]**

8 Answers

1. **A.** Both are CH_2O. Ethanol is C_2H_6O, methanol CH_4O, propanoic acid $C_3H_6O_2$.
2. C: 40.0 ÷ 12.01 = 3.33; H: 6.7 ÷ 1.01 = 6.6; O: 53.3 ÷ 16.00 = 3.33; ratio 1 : 2 : 1 **[1]**. Empirical formula CH_2O (30 g mol^{-1}) **[1]**. 60 ÷ 30 = 2, so the molecular formula is $C_2H_4O_2$ **[1]**.
3. (a) A chain of three carbons with a CH_3 branch on the middle carbon; the end carbon carries the O–H, with every bond (including O–H) drawn **[1]**. (b) A three-point zig-zag with a branch line on the middle point and a line to OH from one end **[1]**.
4. $CH_3COCH(CH_3)CH_3$ **[1]**; $C_5H_{10}O$ **[1]**.
5. **B.** Hexan-1-ol: six carbons, 13 H on carbon and 1 H on oxygen.
6. Advantage: quicker to draw / the carbon skeleton and functional groups are clearer / closer to the real zig-zag shape **[1]**. Disadvantage: H atoms (and C atoms) are not shown, so they must be worked out and can be miscounted **[1]**.
7. Any two: carbon forms four covalent bonds; C–C bonds are strong, so carbon forms stable chains, branches and rings (catenation); carbon forms single, double and triple bonds; it bonds strongly to many other elements (H, O, N, halogens) **[2]**.
8. **B.** $–CONH_2$ is the amido group (an amide).
9. **C.** It contains a C≡C triple bond.
10. (a) carbonyl, aldehyde (b) carbonyl, ketone (c) ester, ester (d) alkoxy, ether (e) amino, amine (f) halogeno (bromo), halogenoalkane **[1]** each.
11. Amino ($–NH_2$) **[1]**; phenyl (benzene ring) **[1]**; ester (–COO–) **[1]**.
12. CH_3CH_2COOH has a carboxyl group (C=O and O–H on the same carbon): a carboxylic acid **[1]**. CH_3COOCH_3 has an ester group (the C=O carbon is joined to O–C, with no O–H): an ester **[1]**.
13. A family of compounds with the same functional group, in which successive members differ by CH_2 **[1]**. Any two characteristics: same general formula; similar chemical properties; gradual trend in physical properties; molar masses differ by 14 g mol^{-1} **[2]**.
14. **B.** Aldehydes share this general formula.
15. **B.** Ethanoic acid is also a carboxylic acid; it differs by two CH_2 units.
16. **D.** I: aldehyde or ketone; II: alcohol or ether; III: carboxylic acid or ester.
17. $14n + 18 = 88$, so $n = 5$: $C_5H_{11}OH$ **[1]**. Next member $C_6H_{13}OH$ **[1]**.
18. The boiling point increases with chain length **[1]**. Each extra CH_2 adds electrons and surface area, so the London dispersion forces get stronger (the hydrogen bonding is similar in each) **[1]**. More energy is needed to separate the molecules **[1]**.
19. **A.** London dispersion only, then dipole–dipole, then hydrogen bonding.
20. Propanoic acid molecules hydrogen bond to each other through the O–H group **[1]**. Methyl ethanoate has no H bonded to O, so it has only dipole–dipole and London dispersion forces **[1]**. Hydrogen bonds are stronger, so more energy is needed to separate the acid molecules **[1]**.
21. 2-Methylbutane is branched, so its molecules are more compact and have a smaller surface area of contact **[1]**. The London dispersion forces are weaker, so less energy is needed to separate them **[1]**.
22. Each extra CH_2 adds the same number of electrons (8), but this is a smaller fraction of the total in a longer molecule **[1]**, so the proportional increase in the London dispersion forces is smaller **[1]**.

23. Melting depends also on how well the molecules pack in the solid lattice, which varies with shape (odd or even number of carbons) **[1]**.

24. Butane < propanal < propan-1-ol **[1]**. Butane has only London dispersion forces; propanal also has dipole–dipole forces from its polar C=O **[1]**; propan-1-ol forms hydrogen bonds through its O–H, the strongest of the three **[1]**.

25. The –OH group forms hydrogen bonds with water **[1]**, but the non-polar hydrocarbon chain cannot, and as the chain gets longer it makes up a larger part of the molecule (and disrupts the hydrogen bonding in water) **[1]**.

26. Propene: CH_2= sp^2, =CH– sp^2, CH_3 sp^3 **[1]**. Propyne: both C≡C carbons sp, CH_3 sp^3 **[1]**.

27. $H_2NCH_2CONHCH(CH_3)COOH$ or $H_2NCH(CH_3)CONHCH_2COOH$, drawn with the –CONH– link **[1]**; peptide bond / amide link **[1]**; water **[1]**.

28. Each amino acid has an amino group and a carboxyl group **[1]**. After a condensation reaction the product still has a free –NH_2 at one end and a free –COOH at the other, so further condensation reactions can add more amino acids at either end **[1]**.

Where this fits in Structure 3.2

- **Booklet 4** (this booklet) — 3.2.1 to 3.2.4: formulas, functional groups and classes, homologous series and the trends in their physical properties.
- **Next** — 3.2.5 and 3.2.6: IUPAC nomenclature and structural isomers; then HL 3.2.7 stereoisomers and HL 3.2.8 – 3.2.9 identifying compounds by mass spectrometry, IR and ^{1}H NMR spectroscopy.
- Links back: **Structure 1.4** (empirical and molecular formulas), **Structure 2.2** (VSEPR shapes, intermolecular forces, HL hybridization). Links forward: **Reactivity 1.2** (combustion), **Reactivity 3.2 – 3.4** (reactions of the functional groups), **Structure 2.4** (polymers, HL condensation).

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