Intermolecular Forces and Functional Groups — Study Guide

Covalent bonds hold atoms together inside a molecule; intermolecular forces (IMFs) hold separate molecules together. IMFs decide whether a compound is a gas, liquid, or solid at room temperature, whether it dissolves in water, and how you separate it in the lab. They are set almost entirely by which functional groups a molecule carries, so this guide pairs the two topics: first the forces, then the master list of functional groups that create them.

Builds on Hybridization, Molecular Geometry, and Polarity. Physical data from the CRC Handbook of Chemistry and Physics and the NIST Chemistry WebBook; concepts from Klein, Clayden, Wade, and McMurry.

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1. The Four Intermolecular Forces

All intermolecular forces are electrostatic: partial or full positive charges attracting partial or full negative charges on neighbouring molecules. They are far weaker than covalent bonds, which is why boiling water breaks only the attractions between H_2O molecules and never the O–H bonds themselves.

Force	Origin	Present in	Typical strength (kcal/mol)
London dispersion	Temporary, induced dipoles from momentary electron fluctuations	Every molecule; the only force in alkanes	~0.1–2 per contact; grows with size and surface area
Dipole–dipole	Attraction between permanent molecular dipoles	Polar molecules: ketones, aldehydes, alkyl halides, ethers	~0.5–2
Hydrogen bonding	H on N, O, or F attracted to a lone pair on N, O, or F	Alcohols, carboxylic acids, amines, amides, water	~1–7 (about 5 in water)
Ion–dipole	An ion attracted to the dipole of a polar molecule	Salts dissolving in water or alcohols	~10–50
For comparison: covalent bond	Shared electron pair	Within molecules	~50–110

Strengths are approximate ranges for a single interaction. The total London force between two large molecules can exceed a single hydrogen bond, because London forces act along the whole length of a molecule. This is why octane (no hydrogen bonds) boils higher than methanol.

London Dispersion Forces

Even in a nonpolar molecule, the electron cloud fluctuates. For an instant one side is slightly negative, and that temporary dipole induces an opposite dipole in a neighbour. Larger molecules have more electrons and larger, more polarisable electron clouds, so their dispersion forces are stronger. Long, straight molecules also have more surface in contact with their neighbours than compact, branched ones.

Dipole–Dipole Forces

Molecules with a permanent dipole moment line up so that the δ+ end of one faces the δ− end of another. The C=O group of aldehydes and ketones (acetone, μ = 2.88 D) is the most important source of dipole–dipole attraction in organic chemistry.

2. Hydrogen Bonding in Detail

A hydrogen bond is a strong dipole–dipole attraction between a hydrogen atom bonded to N, O, or F (the donor) and a lone pair on another N, O, or F (the acceptor). The H is so electron-poor that it behaves almost like a bare proton.

Donor: an H attached to N, O, or F (N–H, O–H, F–H). Acceptor: a lone pair on N, O, or F. A C–H is not a hydrogen-bond donor.

Functional group	Donor?	Acceptor?	Can H-bond with itself?
Alcohol, R–OH	Yes	Yes	Yes
Carboxylic acid, RCOOH	Yes	Yes (two O)	Yes, as cyclic dimers
Primary/secondary amine, RNH_2 / R_2NH	Yes	Yes	Yes
Tertiary amine, R_3N	No	Yes	No (but H-bonds with water)
Primary/secondary amide, $RCONH_2$	Yes	Yes	Yes (very strongly)
Ether, R–O–R	No	Yes	No (but H-bonds with water)
Aldehyde/ketone, C=O	No	Yes	No (but H-bonds with water)

Why O–H Hydrogen Bonds Beat N–H Hydrogen Bonds

Oxygen (EN 3.44) is more electronegative than nitrogen (3.04), so an O–H hydrogen carries a larger δ+. Alcohols therefore boil higher than amines of similar size: ethanol boils at 78 °C, ethylamine at 17 °C.

Carboxylic Acid Dimers

Two carboxylic acid molecules can form two hydrogen bonds to each other at once, creating a cyclic dimer. This effectively doubles the mass of the boiling unit, which is why carboxylic acids have the highest boiling points of any common neutral functional group of similar mass.

Ethers, ketones, aldehydes, esters, and tertiary amines cannot hydrogen-bond with each other, but they can accept hydrogen bonds from water. That is why acetone and diethyl ether dissolve in water much better than hydrocarbons do, even though their boiling points are low.

3. Boiling Points

A liquid boils when its molecules have enough energy to escape their neighbours. Stronger IMFs mean more energy is needed, and a higher boiling point. Three rules predict nearly every comparison you will be asked to make.

- **Compare IMF types first.** At similar molecular weight: ionic > H-bonding > dipole–dipole > London only.
- **Then compare size.** Within one type, a larger molecule (more electrons, more surface) boils higher.
- **Then compare shape.** For isomers, a straight chain boils higher than a branched one.

Rule 1 — Same Mass, Different Forces

Data note. Five compounds with nearly identical molecular weights (72–74 g/mol) span more than 100 °C in boiling point. The dominant intermolecular force, not the mass, sets the order.

Source: Boiling points from the NIST Chemistry WebBook and CRC Handbook: pentane 36.1, diethyl ether 34.6, butanal 74.8, 1-butanol 117.7, propanoic acid 141.2 °C.

Diethyl ether is polar (μ = 1.15 D) but its dipole is small and partly shielded by the ethyl groups, so it boils about where pentane does. Butanal's strong C=O dipole adds ~40 °C. The O–H of 1-butanol adds another ~40 °C through hydrogen bonding, and propanoic acid's hydrogen-bonded dimers push it higher still.

Rule 2 — Bigger Molecules Boil Higher

Data note. Boiling points of the straight-chain alkanes and 1-alcohols from one to eight carbons. Each added CH_2 raises the boiling point by roughly 20–30 °C. The hydrogen-bonding OH matters most in small molecules; by eight carbons, London forces along the chain dominate and the gap narrows from about 226 °C to about 70 °C.

Source: NIST Chemistry WebBook; CRC Handbook of Chemistry and Physics.

Rule 3 — Branching Lowers Boiling Point

Data note. The three isomers of C_5H_{12}. Branching makes the molecule more compact and spherical, so less surface touches neighbouring molecules and London forces weaken.

Source: CRC Handbook: pentane 36.1, 2-methylbutane 27.8, 2,2-dimethylpropane 9.5 °C.

4. Melting Points and Molecular Symmetry

Melting depends on IMFs too, but also on how well molecules pack into a crystal lattice. Compact, symmetrical molecules pack efficiently and are hard to pull out of the lattice, so they melt at higher temperatures. This can reverse the boiling-point trend.

Isomer of C_5H_{12}	Shape	Boiling point (°C)	Melting point (°C)
Pentane	Long, flexible chain	36.1	−129.7
2-Methylbutane	Irregular, one branch	27.8	−159.9
2,2-Dimethylpropane	Compact, highly symmetric sphere	9.5	−16.6

2,2-Dimethylpropane (neopentane) has the lowest boiling point of the three but the highest melting point by more than 100 °C. Its spherical symmetry lets it pack neatly into a crystal, while its small surface area weakens London forces in the liquid.

Exam habit: use IMFs alone for boiling-point questions. For melting points, add a second question: how symmetrical is the molecule? The trans isomer of an alkene, and para-disubstituted benzenes, usually melt higher than their less symmetrical isomers.

5. Solubility: Like Dissolves Like

A substance dissolves when the attractions it forms with the solvent are comparable to the attractions it gives up. Polar and hydrogen-bonding compounds dissolve in polar solvents such as water; nonpolar compounds dissolve in nonpolar solvents such as hexane. Mixing a nonpolar compound into water would break water's hydrogen-bond network without replacing it, which is unfavourable.

The Hydrophobic Chain Wins Eventually

An alcohol has a polar OH head and a nonpolar hydrocarbon tail. Each extra CH_2 makes the molecule more hydrocarbon-like. The rule of thumb is that one polar, hydrogen-bonding group can carry about three to four carbons into water.

> **Data note.** Water solubility of the straight-chain 1-alcohols. Methanol through 1-propanol mix with water in all proportions; beyond that, solubility falls roughly threefold to fourfold with each added carbon.
> Source: Yalkowsky, S. H.; He, Y.; Jain, P. Handbook of Aqueous Solubility Data, 2nd ed.; CRC Press, 2010; and the CRC Handbook. Values near 20–25 °C.

Practical Consequences

- **Extractions:** an organic compound partitions between water and an organic solvent according to polarity. Converting an acid to its salt ($RCOO^-$ Na^+) makes it water-soluble, which is the basis of acid–base extraction.
- **Soaps and detergents** have a long nonpolar tail and an ionic head, so they bridge oily dirt and water.
- **Drug design:** chemists add OH, NH, or ionisable groups to raise water solubility, and add hydrocarbon groups to help a drug cross cell membranes.

Solvent choice in reactions follows the same rule. You met polar protic (water, alcohols) and polar aprotic (acetone, DMSO, DMF) solvents with SN1 and SN2; their behaviour comes directly from whether they can donate hydrogen bonds.

6. The Functional Groups of Organic Chemistry

A functional group is a specific arrangement of atoms that behaves in a predictable way regardless of the rest of the molecule. The hydrocarbon framework is mostly a spectator; the functional groups react. Learning to recognise them on sight is the most important vocabulary skill in the course.

Master Table

Group	Structure	Example	Name ending	Strongest IMF
Alkane	C–C, C–H only	$CH_3CH_2CH_3$ (propane)	-ane	London
Alkene	C=C	$CH_2=CH_2$ (ethene)	-ene	London
Alkyne	C≡C	HC≡CH (ethyne)	-yne	London
Arene (aromatic)	Benzene ring	$C_6H_5CH_3$ (toluene)	-benzene	London
Alkyl halide	C–X (F, Cl, Br, I)	CH_3CH_2Br (bromoethane)	halo- prefix	Dipole–dipole
Alcohol	C–OH (sp^3 C)	CH_3CH_2OH (ethanol)	-ol	H-bonding
Phenol	OH on a benzene ring	C_6H_5OH (phenol)	-phenol	H-bonding
Ether	C–O–C	$CH_3CH_2OCH_2CH_3$ (diethyl ether)	alkoxy- / ether	Dipole (weak); H-bond acceptor
Epoxide	3-membered C–O–C ring	Ethylene oxide	oxirane	Dipole–dipole
Thiol	C–SH	CH_3SH (methanethiol)	-thiol	Weak dipole (S–H H-bonds are weak)
Sulfide	C–S–C	CH_3SCH_3 (dimethyl sulfide)	sulfide	Dipole–dipole
Amine	C–N (no C=O)	CH_3NH_2 (methylamine)	-amine	H-bonding (1°, 2°)
Aldehyde	R–CHO (C=O with ≥ 1 H)	CH_3CHO (ethanal)	-al	Dipole–dipole
Ketone	R–CO–R	CH_3COCH_3 (propanone)	-one	Dipole–dipole
Carboxylic acid	R–COOH	CH_3COOH (ethanoic acid)	-oic acid	H-bonding (dimers)
Ester	R–COO–R′	$CH_3COOCH_2CH_3$ (ethyl ethanoate)	-oate	Dipole–dipole
Amide	R–CONR′$_2$	CH_3CONH_2 (ethanamide)	-amide	H-bonding (1°, 2°)
Acid chloride	R–COCl	CH_3COCl (ethanoyl chloride)	-oyl chloride	Dipole–dipole
Acid anhydride	R–CO–O–CO–R	$(CH_3CO)_2O$ (acetic anhydride)	-oic anhydride	Dipole–dipole
Nitrile	R–C≡N	CH_3CN (ethanenitrile)	-nitrile	Dipole–dipole (strong)
Nitro	R–NO_2	CH_3NO_2 (nitromethane)	nitro- prefix	Dipole–dipole

Three Distinctions Students Mix Up

Look-alikes	How to tell them apart
Alcohol vs phenol	Alcohol OH is on an sp^3 carbon; phenol OH is on a benzene ring. Phenols are about a million times more acidic (pKa 10 vs 16) because of resonance.
Aldehyde vs ketone	Aldehyde C=O carbon carries at least one H (chain end); ketone C=O carbon has two carbons attached (inside the chain).
Amine vs amide	An amide N is bonded directly to a C=O; an amine N is not. Amides are essentially non-basic; amines are bases.
Ether vs ester	An ester O is next to a C=O (R–CO–O–R′); an ether O has two plain alkyl or aryl groups.

The Carbonyl Family

Eight of the groups above contain a C=O. Organic chemistry 2 is organised around them, and you will classify them by what is attached to the carbonyl carbon.

Atoms on the carbonyl carbon	Group
H and C (or two H)	Aldehyde
Two C	Ketone
OH	Carboxylic acid
O–R	Ester
N	Amide
Cl	Acid chloride
O–C(=O)R	Anhydride

7. Finding Functional Groups in Real Molecules

Drugs and natural products contain several functional groups at once. Practise scanning a structure atom by atom: find every heteroatom, then decide what group it belongs to by looking at its neighbours.

Worked Example A — Aspirin (Acetylsalicylic Acid), $C_9H_8O_4$

- **Benzene ring** (arene) bearing two substituents next to each other (ortho).
- **Carboxylic acid** (–COOH) on one ring carbon. It makes aspirin acidic (pKa ≈ 3.5).
- **Ester** (–O–CO–CH_3, an acetate) on the neighbouring carbon. The O attached to the ring is next to a C=O, so it is an ester, not an ether or phenol.

Worked Example B — Acetaminophen (Paracetamol), $C_8H_9NO_2$

- **Phenol**: an OH directly on the ring.

- **Amide**: an N–H bonded to the ring and to a C(=O)CH_3 group. Because the N is attached to C=O, it is an amide, not an amine.

Worked Example C — Lidocaine, $C_{14}H_{22}N_2O$

- **Amide**: an N–H joining the ring to a C=O.
- **Tertiary amine**: a nitrogen with two ethyl groups and one CH_2, with no C=O attached. This basic nitrogen is protonated in the hydrochloride salt used in injections, which makes the drug water-soluble.

Worked Example D — Testosterone, $C_{19}H_{28}O_2$

- **Ketone** conjugated with an **alkene** (an α,β-unsaturated ketone, or enone) in the first ring.
- **Secondary alcohol** on the five-membered ring.
- Everything else is a saturated hydrocarbon framework: four fused rings and two methyl groups.

A fast scanning order: (1) find every C=O and classify it with the carbonyl table; (2) find every O, N, and S not in a carbonyl group; (3) find every C=C, C≡C, and benzene ring. This order avoids the most common mistake, calling an ester O an ether or an amide N an amine.

8. Putting It Together: Ranking Physical Properties

These worked problems combine functional group recognition with IMF reasoning. Work through the three boiling-point rules in order: IMF type, then size, then shape.

Problem 1 — Rank by Boiling Point: Butane, Propanal, 1-Propanol

All three have molecular weights of 58–60 g/mol, so Rule 1 decides.

Compound	Strongest IMF	Boiling point (°C)
Butane, $CH_3CH_2CH_2CH_3$	London only	−0.5
Propanal, CH_3CH_2CHO	Dipole–dipole (C=O)	48
1-Propanol, $CH_3CH_2CH_2OH$	Hydrogen bonding	97

Problem 2 — Isomers of C_3H_9N: How Many N–H Bonds?

All three amines are isomers with the same mass. The number of N–H donors controls the hydrogen bonding.

Compound	Amine type	N–H bonds	Boiling point (°C)
Propylamine, $CH_3CH_2CH_2NH_2$	Primary	2	48
N-Methylethylamine, $CH_3CH_2NHCH_3$	Secondary	1	37
Trimethylamine, $(CH_3)_3N$	Tertiary	0	3

Problem 3 — Isomers of $C_4H_{10}O$: Ether or Alcohol?

Diethyl ether ($CH_3CH_2OCH_2CH_3$) and 1-butanol ($CH_3CH_2CH_2CH_2OH$) have the same formula. The alcohol can donate hydrogen bonds; the ether cannot. Boiling points: 34.6 °C versus 117.7 °C, a difference of 83 °C from one structural change. In water, however, both are moderately soluble (about 6.9 and 7.7 g/100 mL), because the ether oxygen still accepts hydrogen bonds from water.

Problem 4 — Which Dissolves Better in Water: Hexane or 1-Butanol?

Hexane has only London forces and essentially does not dissolve (about 0.001 g/100 mL). 1-Butanol’s OH group hydrogen-bonds with water, and its four-carbon chain is just within the "one polar group per three to four carbons" limit, so about 7.7 g dissolves per 100 mL.

Quick Recap

Concept	Key fact
IMF strength	Ion–dipole > H-bonding > dipole–dipole > London (per interaction, at similar size)
H-bond donor	H on N, O, or F only; C–H never donates
H-bond acceptor	Lone pair on N, O, or F (ethers, ketones, esters accept but do not donate)
Boiling point rules	1) IMF type, 2) size, 3) branching lowers bp
Melting point	IMFs plus packing; symmetric molecules melt higher (neopentane −16.6 °C)
Solubility	Like dissolves like; one polar group carries about 3–4 carbons into water
Functional groups	Classify carbonyls by what is attached to the C=O carbon
Look-alikes	Alcohol vs phenol; aldehyde vs ketone; amine vs amide; ether vs ester

- Identify the strongest IMF before comparing molecular weights

- Count N–H and O–H donors when comparing hydrogen-bonding compounds
- Remember carboxylic acids form hydrogen-bonded dimers
- Scan structures in the order: carbonyls, other heteroatoms, multiple bonds and rings
- Do not call a C–H bond a hydrogen-bond donor
- Do not confuse an amide with an amine or an ester with an ether
- Do not use boiling-point logic alone for melting points; symmetry matters

References & Further Reading

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