

Intermolecular Forces

What forces hold molecules together, and how do they explain boiling points and solubility?

●●○ Intermediate

States of Matter & Gases

Last reviewed 5 October 2026

Before you start: it helps to understand [Molecular Shapes \(VSEPR\)](#) and [Ionic and Covalent Bonds](#).

What is it?

Intermolecular forces are the attractions **between** molecules. They are different from the covalent bonds **within** a molecule (intramolecular forces), and much weaker: boiling water needs 40.7 kJ/mol to separate the molecules, but breaking an O–H bond inside a water molecule needs about 463 kJ/mol.

When a liquid boils, only the intermolecular forces are overcome; the molecules themselves stay intact. So the **stronger** the intermolecular forces, the **higher** the boiling point.

There are three main types, from weakest to strongest (for molecules of similar size):

- **London dispersion forces:** present between **all** molecules. Electrons move constantly, creating brief, temporary dipoles that induce dipoles in neighbouring molecules. They grow with the **number of electrons** (larger molecules) and with **surface contact** (long, unbranched shapes).
- **Dipole–dipole forces:** between **polar** molecules, which have permanent dipoles. The δ^+ end of one molecule attracts the δ^- end of another.
- **Hydrogen bonds:** a strong dipole–dipole attraction between an H atom bonded to **N, O or F** and a lone pair on an N, O or F atom of another molecule.

KEY IDEA

To predict boiling points, ask three questions. Is there an **H on N, O or F**? Then hydrogen bonding. Is the molecule **polar**? Then dipole–dipole forces. How **big** is it? Larger molecules have stronger dispersion forces, which can outweigh the other two.

Why does it matter?

- **States of matter.** Intermolecular forces decide whether a substance is a gas, liquid or solid at room temperature, and its melting and boiling points.

- **Water and life.** Hydrogen bonding gives water its high boiling point, high heat capacity and surface tension, makes ice float, and holds the two strands of DNA together.
- **Solubility and separation.** “Like dissolves like” and chromatography both depend on matching intermolecular forces.

How does it work?

1. Dispersion forces and molecular size

The halogens are non-polar, so they have only dispersion forces. As the molecules get bigger and have more electrons, the dispersion forces grow and the boiling points rise:

Halogen	Molar mass	Boiling point	State at 25 °C
F ₂	38.00 g/mol	−188 °C	gas
Cl ₂	70.90 g/mol	−34 °C	gas
Br ₂	159.80 g/mol	59 °C	liquid
I ₂	253.80 g/mol	184 °C	solid

Shape matters too: unbranched pentane (36 °C) boils higher than compact 2,2-dimethylpropane (10 °C), because long molecules touch over a larger area.

2. Comparing molecules of similar size

When molar masses are similar, dispersion forces are similar, and the other forces decide:

Compound	Molar mass	Strongest force	Boiling point
butane, CH ₃ CH ₂ CH ₂ CH ₃	58.12 g/mol	dispersion	about 0 °C
propanone, CH ₃ COCH ₃	58.08 g/mol	dipole–dipole	56 °C
propan-1-ol, CH ₃ CH ₂ CH ₂ OH	60.10 g/mol	hydrogen bonding	97 °C

3. Hydrogen bonding

Hydrogen bonding is unusually strong because N, O and F are very electronegative and small, and the H atom has no inner electrons, so its nucleus is exposed. Each water molecule can form up to four hydrogen bonds (two through its H atoms and two through its lone pairs). That is why:

- water (18.02 g/mol) boils at 100 °C, while H₂S (34.08 g/mol) boils at −60 °C;
- **ice floats:** in ice, hydrogen bonds hold the molecules in an open hexagonal network, so ice is less dense than liquid water.

4. Effects on properties

Stronger intermolecular forces mean:

- higher **melting** and **boiling points** and a larger **enthalpy of vaporization**;
- lower **vapour pressure** (fewer molecules escape from the liquid);
- higher **viscosity** and **surface tension**.

For solubility, a solute dissolves best in a solvent with **similar** forces: polar and hydrogen-bonding substances (sugar, ethanol) dissolve in water; non-polar substances (oil, iodine) dissolve in non-polar solvents such as hexane. Ionic compounds dissolve in water through **ion-dipole** attractions.

∞ THINK OF IT LIKE THIS

Think of molecules as people in a crowded room. Dispersion forces are a light brush of shoulders: weak, but they add up when people are big and pressed close together. Dipole-dipole forces are like people turning to face each other. Hydrogen bonds are firm handshakes. The more handshakes, the harder it is for anyone to leave the room, just as more hydrogen bonding makes a liquid harder to boil.

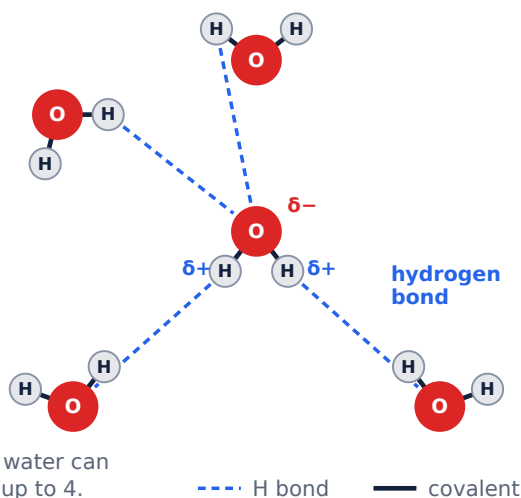
Q MORE PRECISELY

Dispersion forces are not always the weakest overall: a large non-polar molecule can have stronger total attractions than a small polar one. Iodine (I_2 , 184 °C) boils far higher than water, despite having no dipole. A hydrogen bond is typically 10 to 40 kJ/mol, compared with roughly 150 to 1000 kJ/mol for covalent bonds. In proteins, hydrogen bonds between different parts of the chain hold the shapes (helices and sheets) that make the protein work.

Visualise it

Hydrogen bonds between water molecules

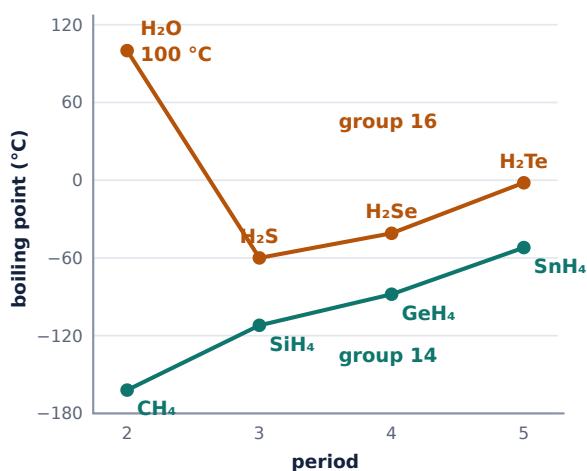
$\delta+$ hydrogen on one molecule, lone pair on $\delta-$ oxygen of the



Dashed lines are hydrogen bonds: much weaker than the covalent O–H bonds, but strong for an intermolecular force.

Boiling points of the hydrides

Water is far higher than the trend predicts: hydrogen bonding



Extending the trend, water would boil at about -80°C .

Boiling points rise with molecular size (dispersion forces), except for water, which hydrogen bonding lifts far above the trend.

Worked example

WORKED EXAMPLE: Identifying intermolecular forces

Question: Name all the intermolecular forces in (a) CH₄ (b) HCl (c) NH₃ (d) CO₂.

Step 1 (a) Non-polar: **dispersion forces only**.

Step 2 (b) Polar (Cl is more electronegative than H), but H is not on N, O or F: **dispersion + dipole–dipole**.

Step 3 (c) H bonded to N, and N has a lone pair: **dispersion + dipole–dipole + hydrogen bonding**.

Step 4 (d) The C=O bonds are polar, but the linear molecule is symmetrical, so the dipoles cancel: **dispersion forces only**.

WORKED EXAMPLE: Ranking boiling points

Question: Put butane, propanone and propan-1-ol in order of increasing boiling point, and explain.

Step 1 Their molar masses are almost equal (58 to 60 g/mol), so their dispersion forces are similar.

Step 2 Butane is non-polar: dispersion only. **Lowest**.

Step 3 Propanone has a polar C=O group: dipole–dipole forces as well. **Middle**.

Step 4 Propan-1-ol has an O–H group: hydrogen bonding as well. **Highest**.

Step 5 Order, lowest first: **butane (about 0 °C), propanone (56 °C), propan-1-ol (97 °C)**.

WORKED EXAMPLE: Energy to boil water

Question: How much energy is needed to vaporize 25.0 g of water at 100 °C? ($\Delta H_{\text{vap}} = 40.7 \text{ kJ/mol}$; H₂O = 18.02 g/mol)

Step 1
$$n = \frac{25.0 \text{ g}}{18.02 \text{ g/mol}} = 1.387 \text{ mol}$$

Step 2
$$q = n \times \Delta H_{\text{vap}} = 1.387 \text{ mol} \times 40.7 \text{ kJ/mol} = 56.5 \text{ kJ}$$

Step 3 This energy only separates the molecules (overcoming hydrogen bonds and other intermolecular forces); no O–H bonds are broken, and the steam is still H₂O.

Common mistake

COMMON MISTAKE: Thinking boiling breaks covalent bonds

When water boils, the bubbles contain H_2O molecules, not hydrogen and oxygen. Boiling overcomes **intermolecular** forces; the covalent bonds inside the molecules are untouched.

COMMON MISTAKE: Calling any H-containing molecule hydrogen-bonded

Hydrogen bonding needs H bonded **directly** to N, O or F. CH_4 and the C-H hydrogens in ethanol do not form hydrogen bonds; only ethanol's O-H hydrogen does.

COMMON MISTAKE: Forgetting dispersion forces

Every molecule has dispersion forces, including polar ones. For large molecules they are often the largest contribution: that is why iodine is a solid and HBr boils higher than HCl .

NOTATION NOTE

- London dispersion forces are also called London forces, dispersion forces or instantaneous dipole-induced dipole forces. Together with dipole-dipole forces they are often called van der Waals forces.
- A hydrogen bond is usually drawn as a dashed line: $\text{O}-\text{H}\cdots\text{O}$.
- δ^+ and δ^- mean partial positive and partial negative charges.

Remember this

REMEMBER THIS

- Intermolecular forces act between molecules; they are much weaker than covalent bonds. Boiling overcomes only these forces.
- For molecules of similar size, weakest to strongest: dispersion (all molecules; bigger and longer = stronger), dipole-dipole (polar molecules), hydrogen bonding (H on N, O or F).
- Stronger forces: higher boiling point, lower vapour pressure, higher viscosity and surface tension.
- Like dissolves like; hydrogen bonding explains water's high boiling point and why ice floats.

References

1. Brown, T. L.; LeMay, H. E., Jr.; Bursten, B. E.; Murphy, C. J.; Woodward, P. M.; Stoltzfus, M. W. Chemistry: The Central Science, 15th ed.; Pearson, 2022.

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