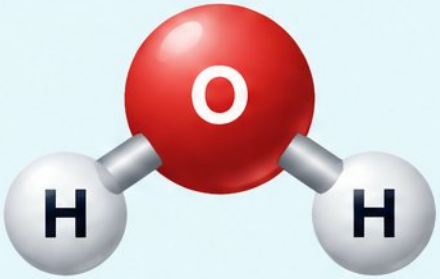
Intermolecular Forces:
Why Water Behaves Unusually

- **Hook:** water boils at 100 °C; methane boils at −162 °C and hydrogen sulfide at −60 °C.
- Ice floats on liquid water — unusual for a solid.
- **Core question:** what holds molecules together without chemical bonds?
- **Roadmap:** bond types → hydrogen bonding → water's anomalies → solvent behavior → demos → recap.



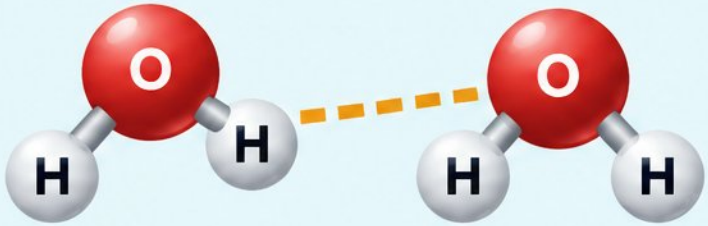
Intramolecular Bonds Versus Intermolecular Forces

Within One Water Molecule (Intramolecular Bond)



Covalent O–H Bonds
(within one molecule)

Between Two Water Molecules (Intermolecular Force)



Hydrogen Bond
(between molecules)

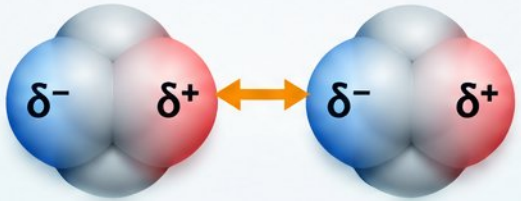
Energy Scale (Relative)

- Covalent Bond (O–H)
- Hydrogen Bond
- Dispersion Force

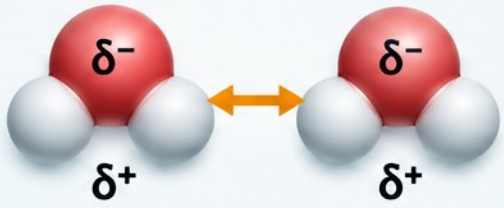
- Intra = within a molecule: covalent O–H bonds hold H_2O together
- Inter = between molecules: attractions that hold separate molecules close
- Breaking both O–H bonds in 1 mol water: about 927 kJ
- Vaporizing 1 mol water: only about 41 kJ
- A hydrogen bond is about 20 kJ/mol, not a covalent bond
- These forces set boiling point, melting point, viscosity, surface tension, solubility
- **Misconception: boiling does not break O–H bonds; steam is intact H_2O**

The Main Types of Intermolecular Forces

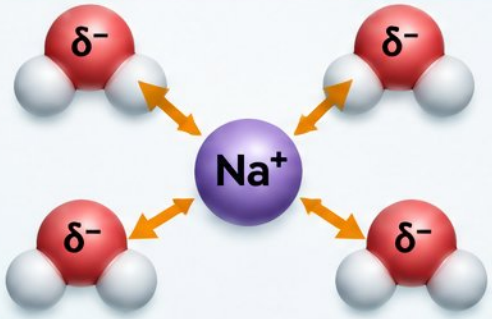
London dispersion



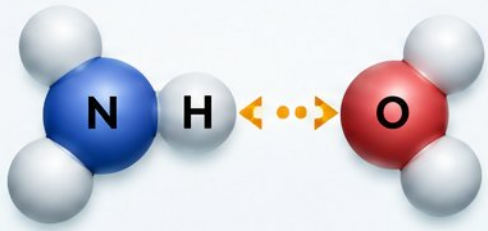
Dipole–dipole



Ion–dipole



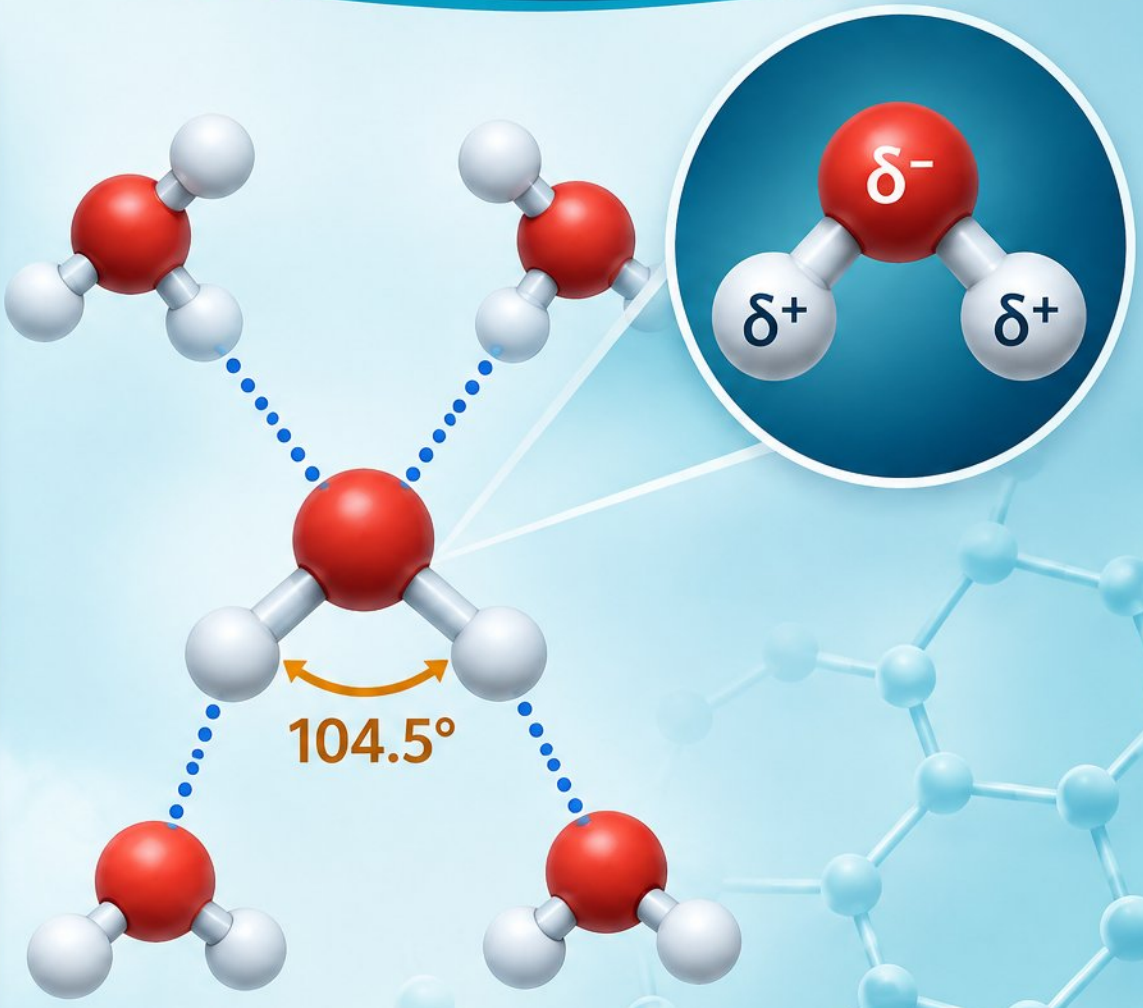
Hydrogen bonding



- **London dispersion:** temporary dipoles in all molecules; stronger with more electrons and contact area
- **Dipole–dipole:** permanent δ^+ to δ^- alignment in all polar molecules
- **Ion–dipole:** full ion charge attracts a polar molecule (Na^+ in water); strongest, 40–600 kJ/mol
- **Hydrogen bonding:** H on N, O, or F meets a lone pair; extra-strong dipole–dipole
- **Ranking (similar size):** dispersion < dipole–dipole < hydrogen bonding
- **Exception:** large molecules' dispersion can beat H-bonding (I_2 solid, water liquid)

Hydrogen Bonding in Water: Geometry and Network

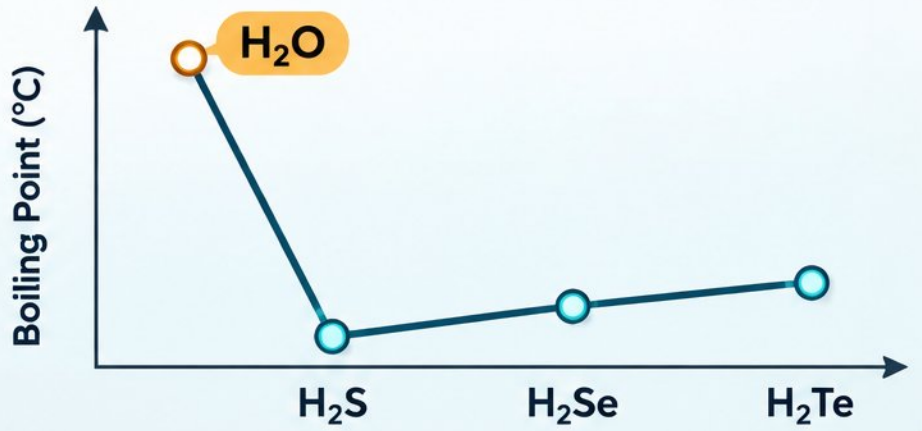
- O–H bonds are polar: δ⁻ oxygen, δ⁺ hydrogens; bent 104.5° shape.
- Two H donors plus two lone-pair acceptors give up to four bonds.
- In ice: four neighbors, O···O ≈ 2.76 Å, O–O–O ≈ 109°.
- In liquid water: roughly 3.4–3.5 partners, breaking and re-forming in picoseconds.
- The O–H···O hydrogen bond is nearly linear (about 180°).



Anomaly 1: Boiling Point, Melting Point, and Heat Capacity

- Water boils at 100 °C; trend from H_2S to H_2Te predicts about −80 to −130 °C without hydrogen bonding.
- Heat of vaporization: water 40.7 kJ/mol, H_2S 18.7, CH_4 8.9; specific heat ~4.18 J/(g·°C).
- Hydrogen bonds must break before molecules escape as gas—hence the extra energy needed.
- NH_3 (−33 °C) and HF (20 °C) also sit above hydride trends; water's jump is largest.
- **Consequences:** water moderates climate and body temperature; sweat cools by evaporation.

Boiling-Point Trend: Group 16 Hydrides

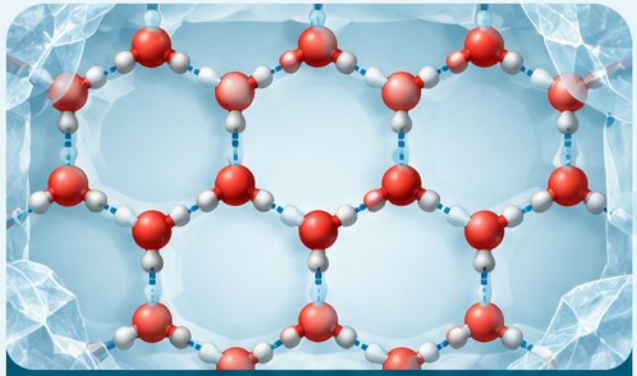


Heat of Vaporization

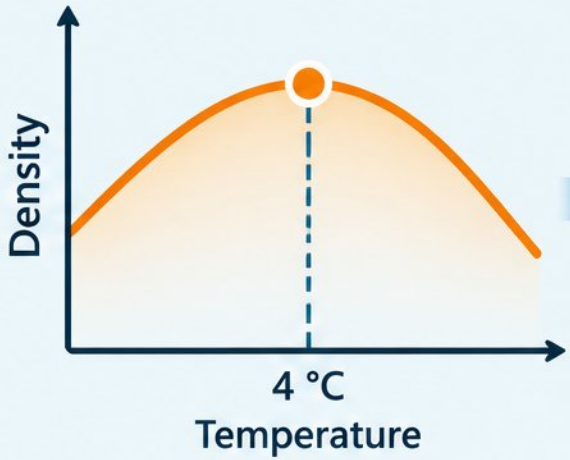


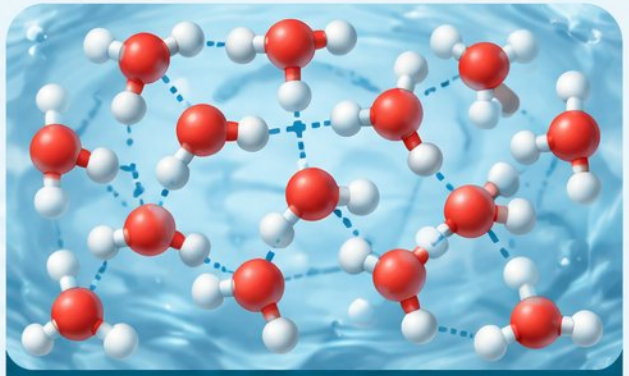


Anomaly 2: Why Ice Floats and Water Peaks at 4 °C



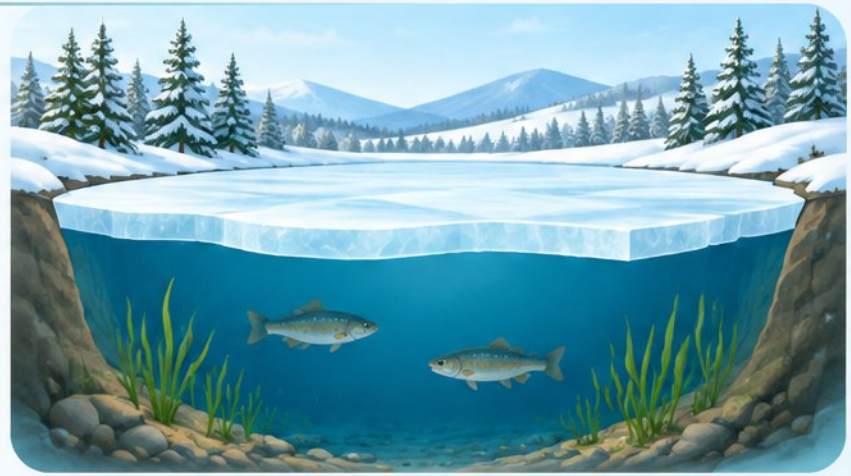
Hexagonal ice (Ih)
(open lattice with large cavities)





Liquid water
(more closely packed, denser)

- **Ice density** ≈ 0.917 g/cm³ vs **liquid water** ≈ 1.000 g/cm³ at 4 °C
- **Hexagonal ice (Ih):** tetrahedral hydrogen bonds build an open lattice with large cavities
- **Melting** partly collapses this open cage, so liquid water packs closer and is denser
- Below 4 °C, growing hydrogen-bond order expands water; above 4 °C, thermal expansion dominates
- **Lakes freeze top-down;** ice insulates the water below and protects aquatic life
- **Seasonal turnover** follows the 4 °C density maximum











Anomaly 3: Cohesion, Adhesion, Surface Tension, and Capillarity

- **Cohesion:** water–water hydrogen bonds pull the surface into the smallest area — high surface tension
- Surface tension supports a steel needle or paper clip; water striders walk on it
- **Adhesion:** water sticks to polar surfaces like glass –OH groups; cohesion vs. adhesion sets contact angle
- **Capillary action:** when adhesion beats cohesion, water climbs paper towels, straws, and plant xylem
- **Meniscus:** water creeps up glass (concave); mercury sinks (convex); detergents lower surface tension



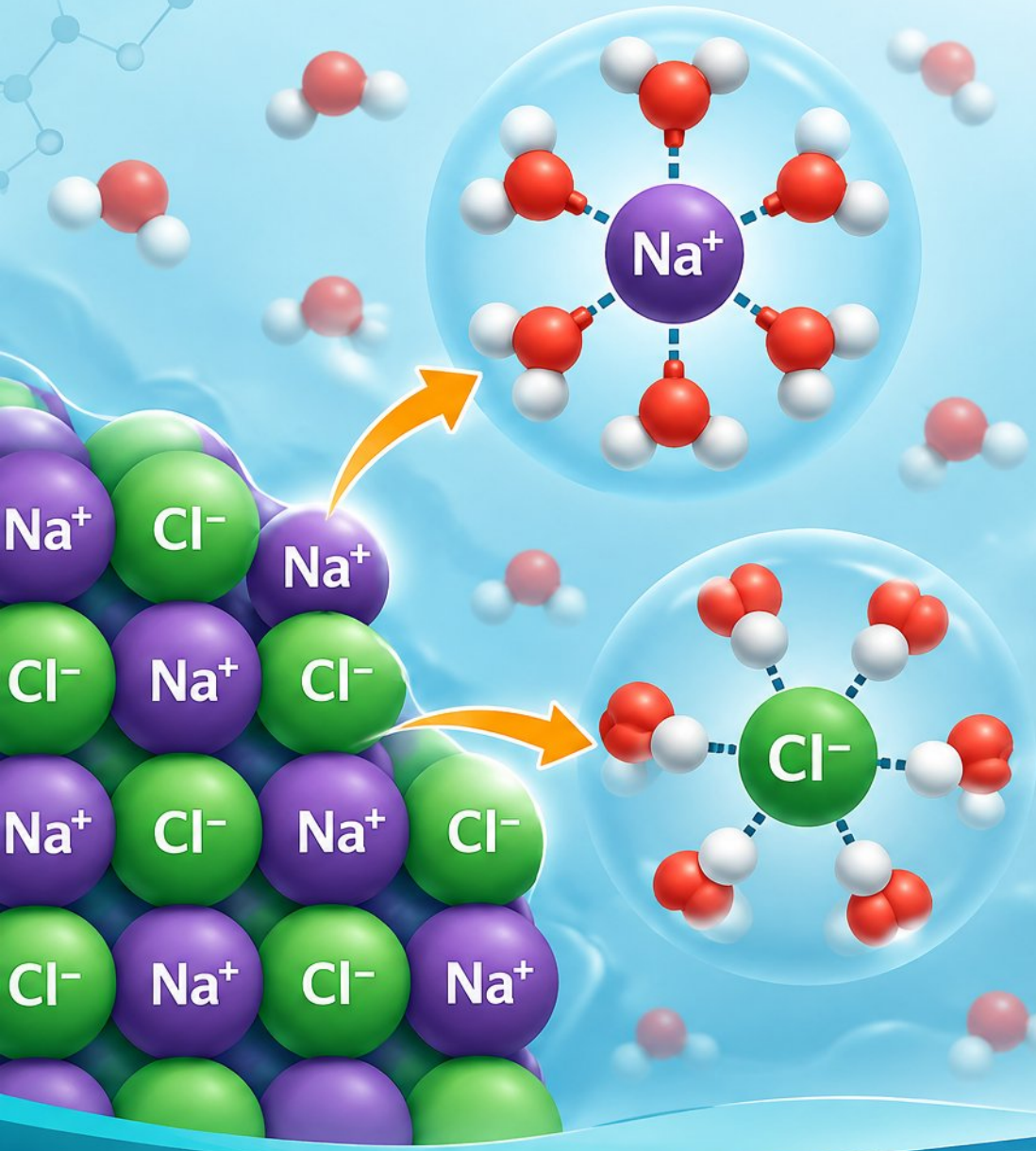








Water as a Solvent: Ion–Dipole Forces and Hydration

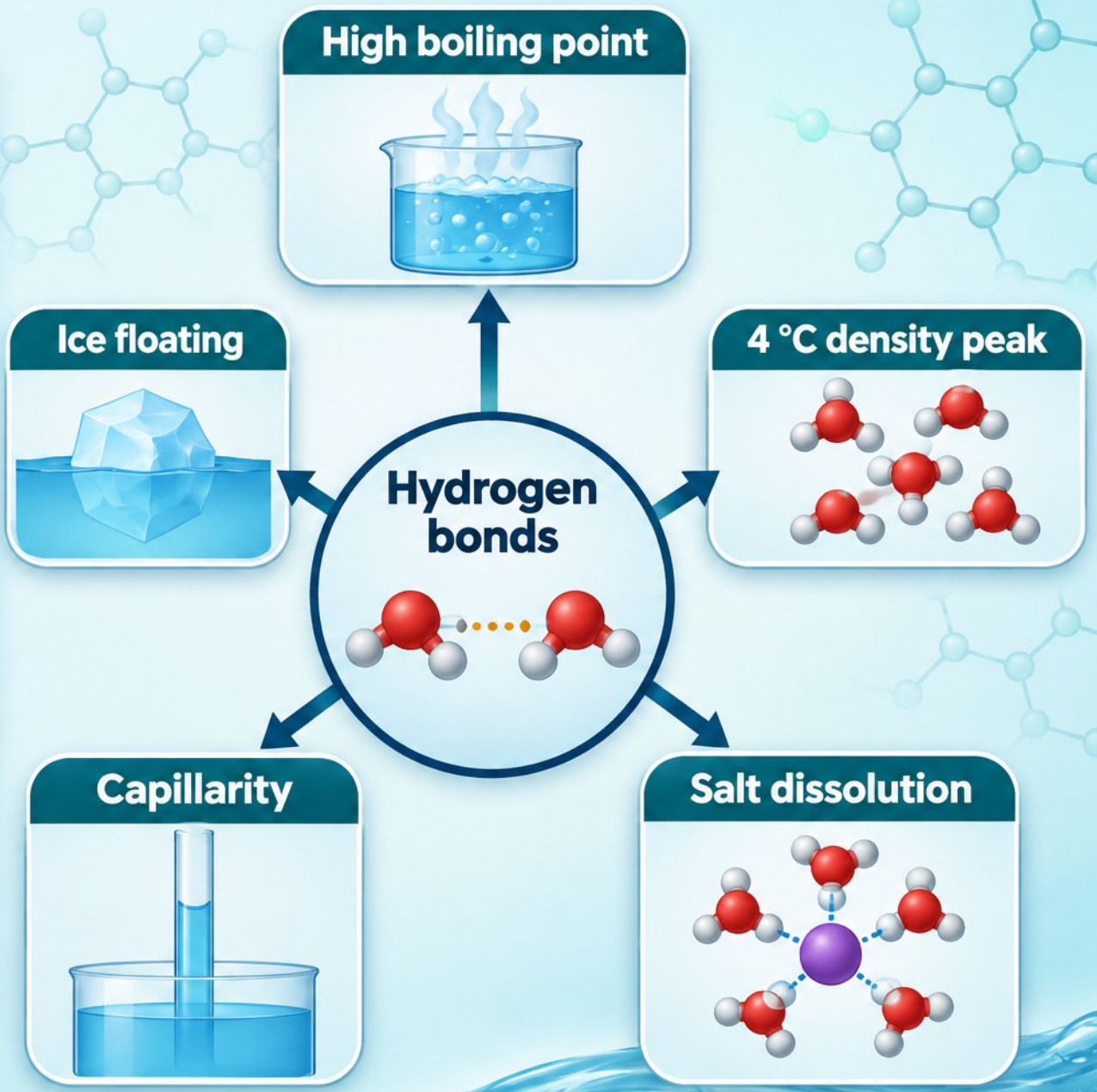


- Water's dipole (1.85 D) orients O at Na^+, H at Cl^-, pulling ions free
- Ion–dipole attraction is the strongest intermolecular force
- Hydration shells surround each ion, keeping the lattice from re-forming
- Energy balance: lattice 773 kJ/mol vs hydration 769 kJ/mol → +4 kJ/mol
- Like dissolves like: polar/ionic solutes dissolve; grease and oil do not
- Dissolved ions carry current, so electrolyte solutions conduct

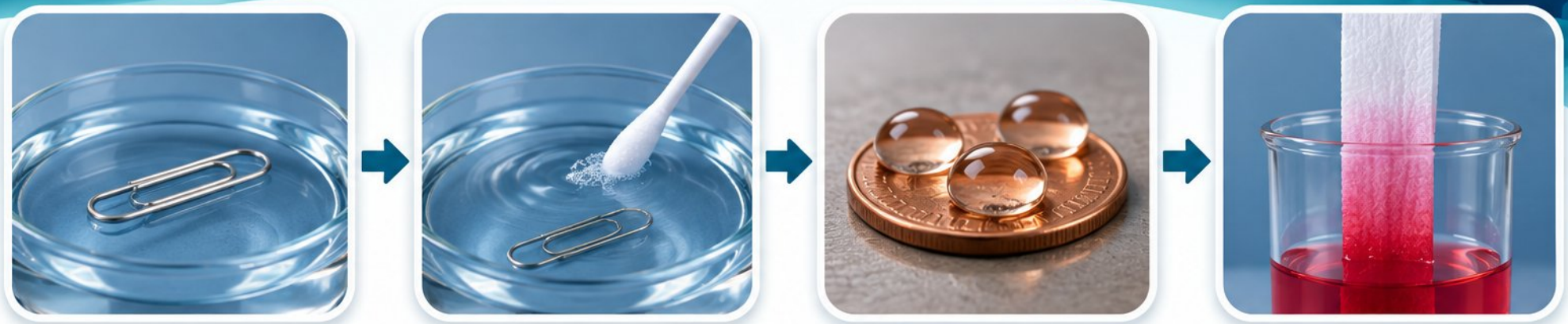
Bringing It Together: Force-to-Anomaly Map

- Hydrogen bonds (~20 kJ/mol) → high boiling point, high heat of vaporization
- Tetrahedral bonding → open ice lattice → ice floats; collapse → density peak at 4 °C
- Cohesion + adhesion → high surface tension → capillary action
- Ion–dipole + hydration shells → salts dissolve; electrolytes conduct

- **Unifying takeaway: hydrogen bonding explains all of water's headline anomalies**



Demo Toolkit Part 1: Surface Tension and Capillarity



- **Demo 1:** Float a paper clip or needle; touch with soap—it sinks.
- **Demo 2:** Count water drops on plain, waxed, and soapy pennies.
- **Demo 3:** Paper towel or narrow tube in colored water—water climbs up.
- **Demo 4:** Pepper on water; add one soap drop—pepper scatters.

Safety: goggles, wash hands; handle needles point-in-card, rinse beakers.

Debrief each demo: which force was overcome, which anomaly shown?

Everyday Consequence



Demo Toolkit Part 2: Density and Dissolving

Demo 5



Ice cube in dyed water—it floats; a frozen block of another substance sinks in its own liquid

Demo 6



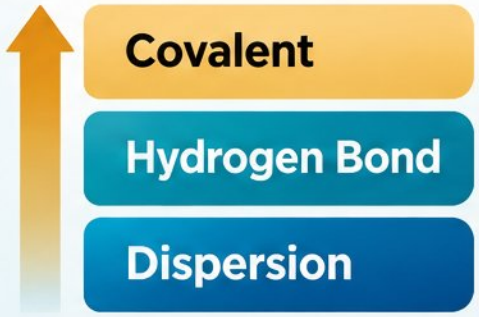
Stir salt into water—temperature barely changes (lattice ≈ 773 kJ/mol, hydration ≈ 769 kJ/mol)

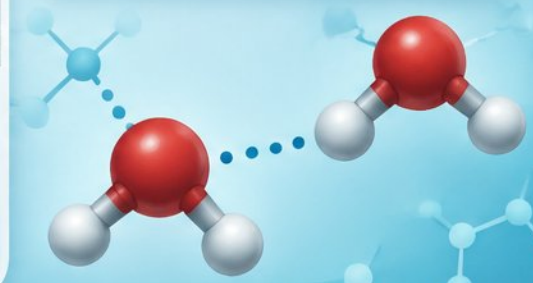
Demo 7



Salt or sugar in water tersus oil in water—layers and droplets show 'like dissolves like'

Energy Scale

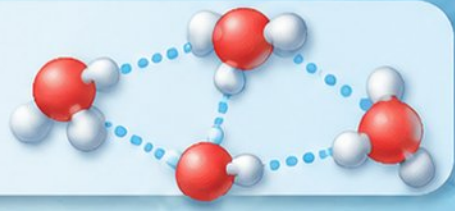




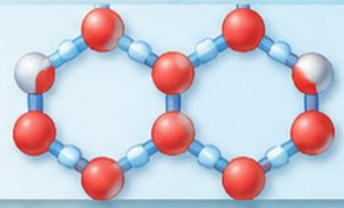
- **Force link:** ion–dipole (salt), hydrogen bonding (sugar/alcohol), dispersion (oil)
- **Predict:** boiling order of CH_4, H_2S, H_2O; why ice floats; will a substance dissolve?
- **Misconception checks:** hydrogen bonds are covalent; boiling breaks water molecules; ice floats because it is colder

Common Misconceptions and How to Address Them

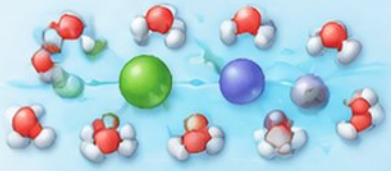
~~"Hydrogen bonds are covalent"~~	they are ~5–10% as strong; breaking them keeps H_2O intact.
~~"Boiling splits water"~~	steam is unbroken H_2O; only intermolecular forces are overcome.
~~"Ice floats because it's cold"~~	the open tetrahedral lattice lowers ice's density.
~~"Bigger always means stronger"~~	dispersion grows with electrons and contact area, but H-bonding can dominate.
~~"Dissolving salt breaks ionic bonds"~~	ion–dipole forces separate pre-existing ions.







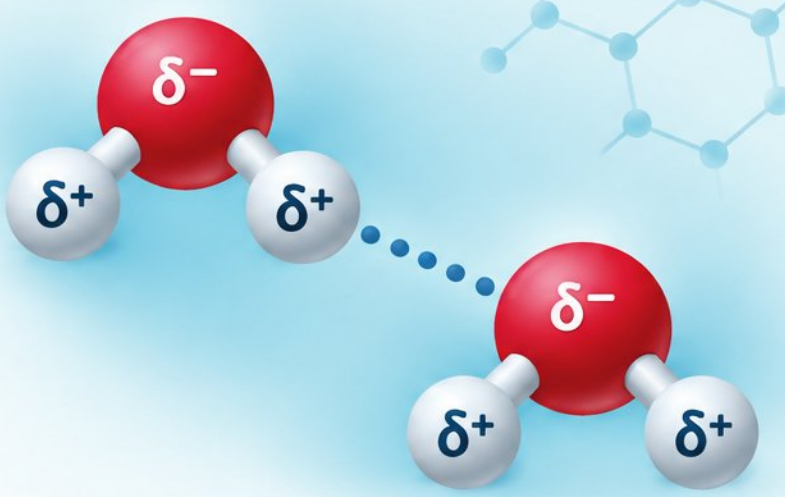




Teaching move: name the force, compare strengths, state what must be overcome.

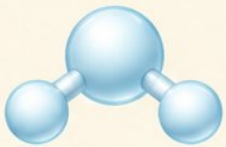
Recap: Key Takeaways

- Intermolecular forces are weak versus covalent bonds, yet they set boiling points, density, surface behavior, and solubility.
- Hydrogen bonding is the single unifying explanation for water's unusual behavior.
- Water boils about 175 °C above the predicted Group 16 trend, has high heat of vaporization and heat capacity, and ice is less dense than liquid water.



Force	Role	Anomaly
hydrogen bonds	high boiling point	high boiling point
tetrahedral network	floating ice	floating ice
cohesion + adhesion	capillary action	capillary action
ion–dipole	dissolving salts	dissolving salts

Exit ticket: "Water behaves unusually because…" name the force and give one piece of evidence.



Check Your Understanding and Where to Go Next

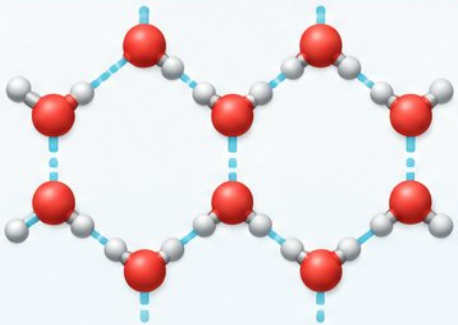
Q1: Rank boiling points of CH_4, H_2S, H_2O; name the dominant force.



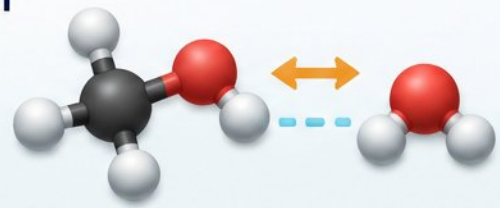
Q2: Why does a needle float—and sink when soap is added?



Q3: Why does ice float, and why do lakes freeze top-down?



Q4: Predict water solubility of NaCl, ethanol, and cooking oil.



Rubric: name the force, compare strength, state what must be overcome.

Extensions: hydrogen bonding in DNA and proteins; climate modeling; desalination.

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