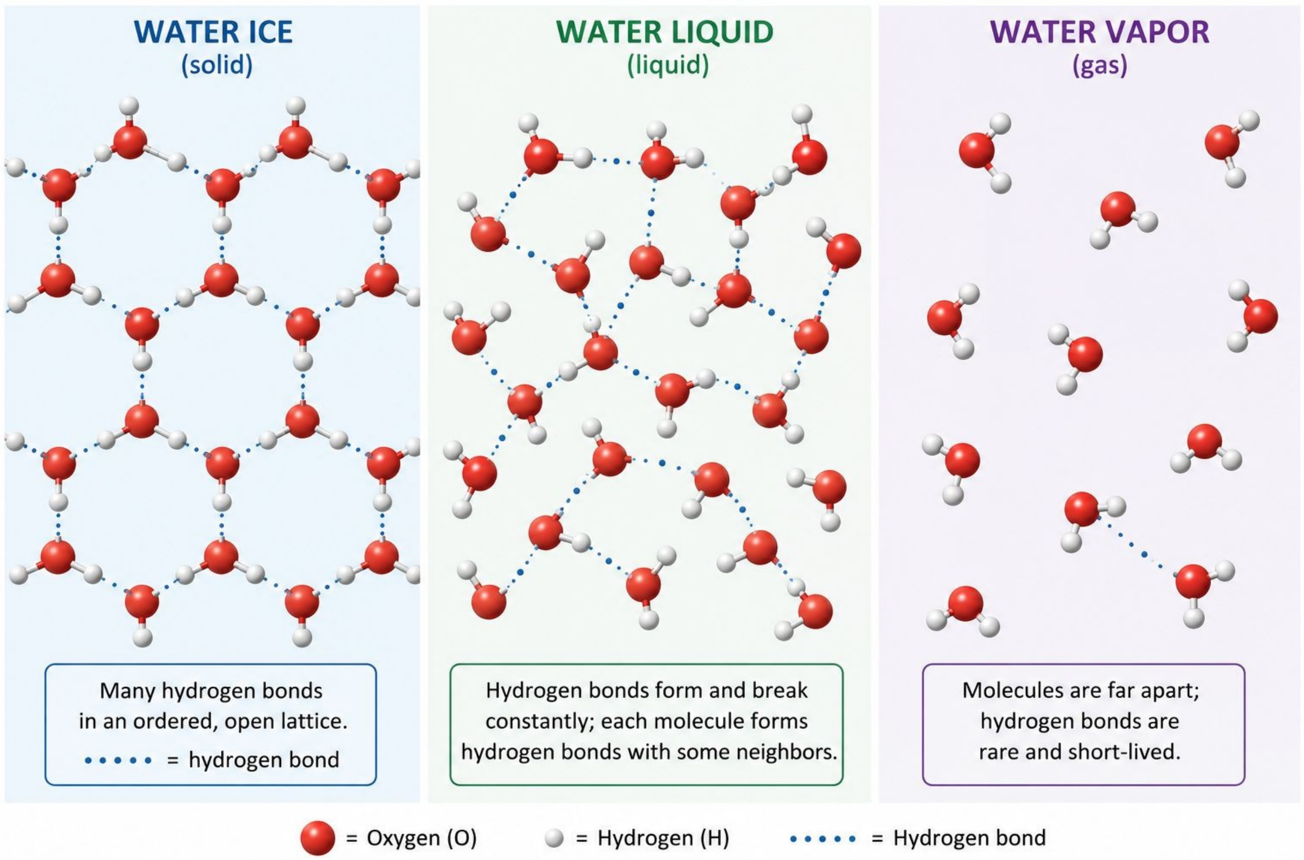
HYDROGEN BONDS IN WATER

Why ice floats, liquid flows, vapor spreads—and salt melts ice

THE ONE IDEA A water molecule stays H_2O in every phase. What changes is how neighboring molecules are arranged and how long their hydrogen-bond connections persist.

A six-part picture sequence

1 The bond	2 Ice	3 Liquid	4 Vapor	5 4°C density	6 Salt + ice



OVERVIEW • Ice has an ordered network; liquid water has a changing network; vapor molecules are usually far apart.

READ THE DOTTED LINES They represent hydrogen bonds between neighboring H_2O molecules—not the strong O–H covalent bonds inside a molecule.

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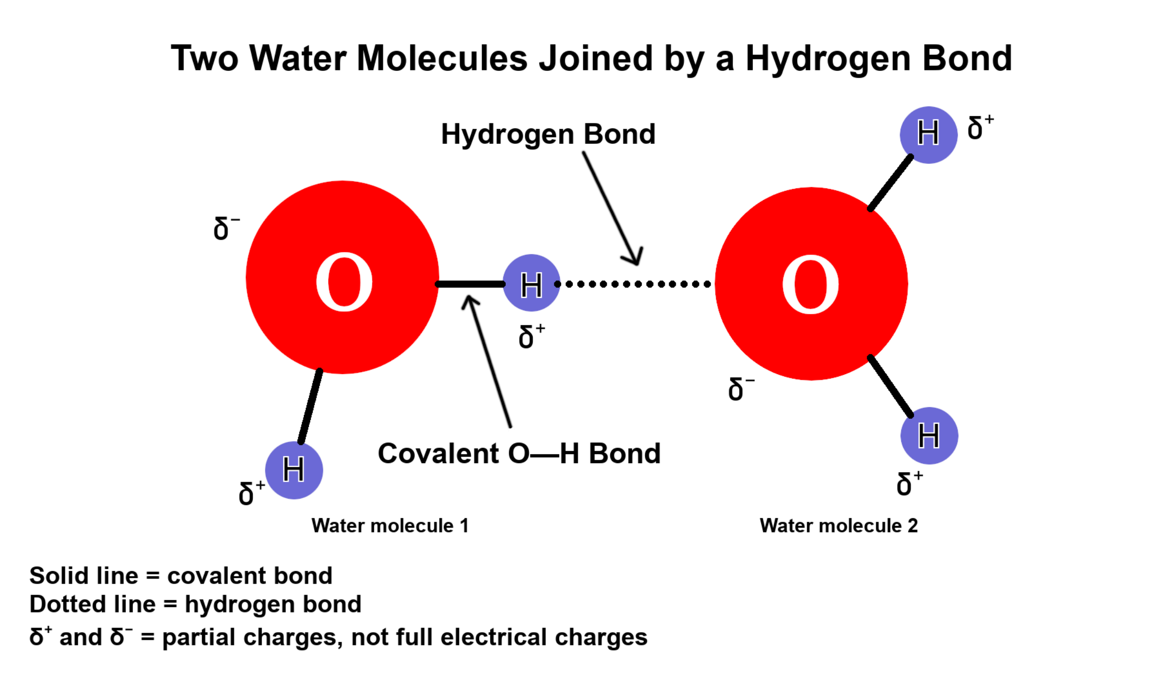
1 WHAT IS A HYDROGEN BOND?

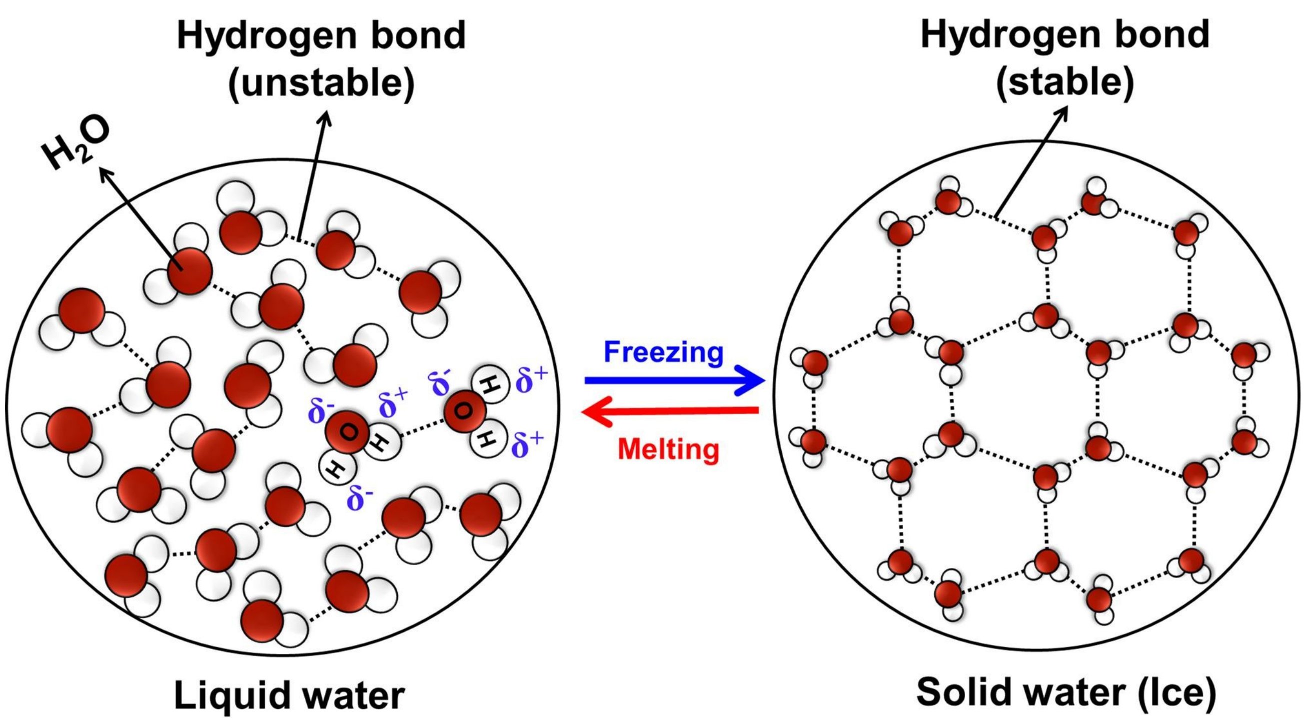
Start with one connection between two molecules, then build outward to the network.



Solid lines stay inside each H_2O molecule. The dotted line connects neighboring molecules.

POLAR MOLECULE	BETWEEN MOLECULES	THREE-DIMENSIONAL
Oxygen carries a partial negative charge (δ−); the hydrogens carry partial positive charges (δ+).	A partly positive H is attracted to a neighboring O. That intermolecular attraction is the hydrogen bond.	Each H_2O can participate in several hydrogen bonds, allowing large networks to form and rearrange.

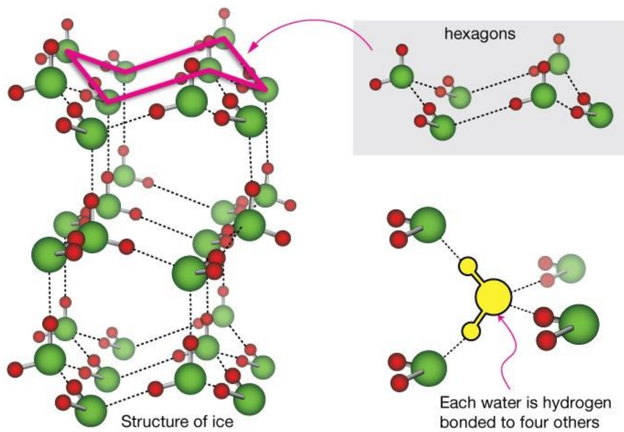
Freezing builds long-range order; melting removes that order



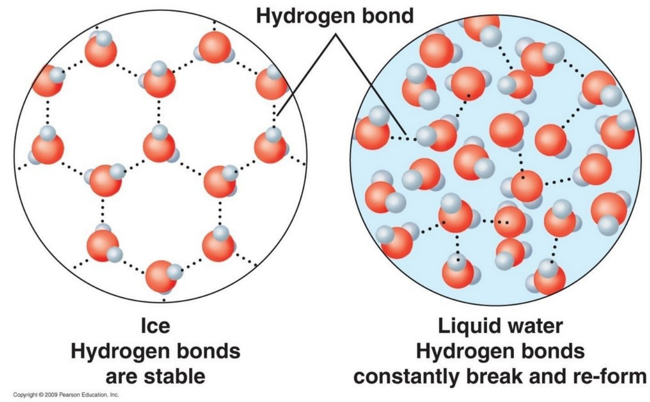
YOUR SELECTED COMPARISON • “Unstable” here means temporary and changing—not that liquid water lacks hydrogen bonds.

2–4 HOW THE NETWORK CHANGES

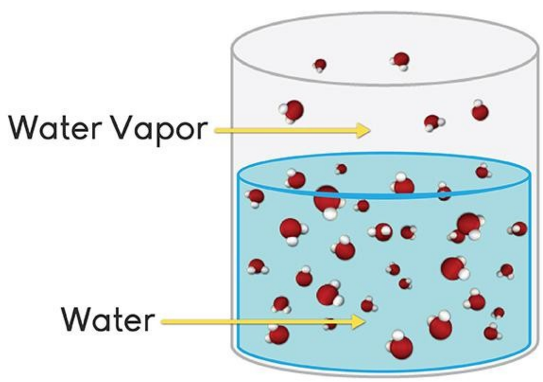
The phases differ mainly in arrangement, persistence, and freedom of motion.



2 ICE ● Open, repeating crystal structure.



3 LIQUID ● Close-packed, changing neighbors.



4 VAPOR ● Molecules are usually far apart.

ICE Molecules mostly vibrate around fixed positions. A persistent hydrogen-bond network maintains long-range crystal order.

LIQUID Many hydrogen bonds remain, but partners change as molecules rotate, jostle, and diffuse. Network rearrangement occurs on picosecond time scales.

VAPOR Molecules move freely between collisions. Brief pairs or clusters can occur, but ordinary low-pressure vapor is mostly not hydrogen-bonded.

REMEMBER Water vapor is invisible. A visible cloud is made of tiny liquid droplets and/or ice crystals.

THE MOTION DISTINCTION Ice molecules are not motionless, liquid molecules do not lose every hydrogen bond, and vapor molecules are not visible as a cloud.

MOLECULAR MOTION: SPEED, COLLISIONS, AND TRAVEL

Approximate phase-appropriate values reveal why instantaneous speed and net displacement are very different measurements.

REFERENCE CONDITIONS Ice: −10°C (14°F), ordinary hexagonal ice. Liquid: 21°C (70°F). Vapor: 21°C water vapor diffusing through still air at one atmosphere. Results are teaching-scale estimates, not exact universal constants.

MEASUREMENT	ICE	LIQUID WATER	WATER VAPOR
Mean instantaneous molecular speed	≈1,830 ft/s	≈1,930 ft/s	≈1,930 ft/s
"Collisions" or nearest-neighbor encounters per second	No gas-style collisions; ≈10^{12}–10^{13} lattice vibrations/s	No discrete impacts; ≈10^{13} close-neighbor jostles/s	≈5×10^{9} collisions/s with surrounding air molecules
Displacement after one second	Vibrates ≈10^{-8}–3×10^{-8} mm about its lattice site; net travel ≈0	≈0.12 mm RMS (0.005 in)—about one or two human-hair widths	≈12 mm RMS (0.47 in) through air, despite a zigzag path totaling ≈1,930 ft
Hydrogen bonds breaking and reconnecting per second	For most bulk molecules, ≈0 lasting partner exchanges during one second; surface and defects are faster	≈10^{11}–10^{12} partner exchanges/s; the precise value depends on the H-bond definition	≈0 sustained bonds for most molecules; transient-event rate depends strongly on humidity and pressure
What the motion looks like	Fast vibration with repeated reversal around a fixed site	Fast jostling plus slow random diffusion through changing neighbors	Longer free paths between collisions; direction randomized by air

How to read the table

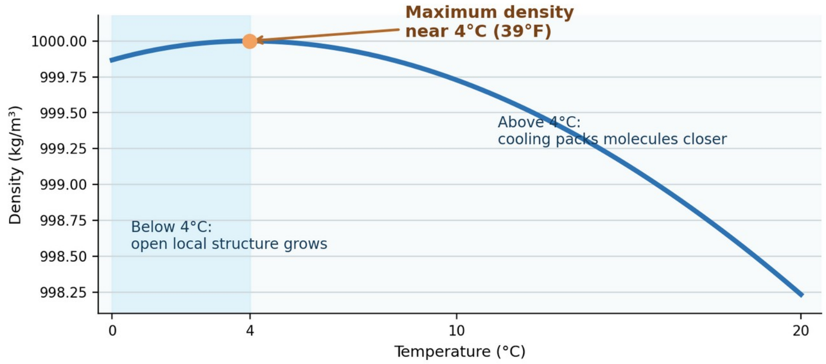
SAME SPEED SCALE	DIFFERENT DIRECTION CHANGES	DIFFERENT BOND NETWORKS
At a given temperature, molecular center-of-mass velocities are on roughly the same thermal scale in every phase.	The speedometer-like number counts all forward and backward motion. It does not measure progress away from the starting point.	Ice mostly keeps the same partners; liquid water rapidly exchanges partners; ordinary vapor is mostly unbonded.

CALCULATION NOTE Mean thermal speed uses $\bar{v} = \sqrt{8RT/\pi M}$. Random displacement uses RMS distance = $\sqrt{6Dt}$. "Collision" is well defined for a dilute gas but not for condensed water, whose neighbors interact continuously.

Data basis: Krynicki, Green & Sawyer, Faraday Discuss. (1978), doi:10.1039/DC9786600199 • Liu et al., Sci. Adv. (2017), PMCID: PMC5885775 • NIST Technical Note 2279 (2024), gas diffusion coefficients.

5 WHY WATER IS DENSEST NEAR 4°C (39°F)

Two competing effects cross over near 4°C: thermal contraction and increasingly open hydrogen-bond structure.

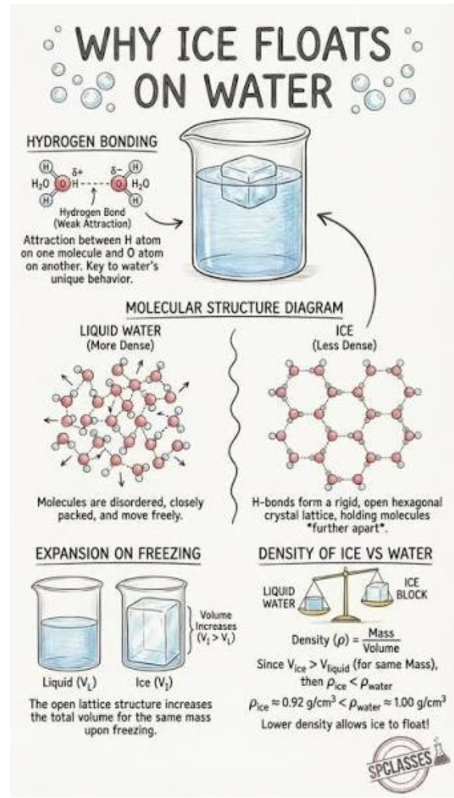


Pure liquid water reaches maximum density near 3.98°C at ordinary pressure.

ABOVE 4°C Cooling reduces disruptive thermal motion and allows closer average packing, so density rises.

BELOW 4°C More open, locally tetrahedral arrangements develop. Average spacing grows, so density falls.

AT FREEZING The open structure becomes a long-range crystal. Water expands by about 9%, making ordinary ice less dense than liquid water.

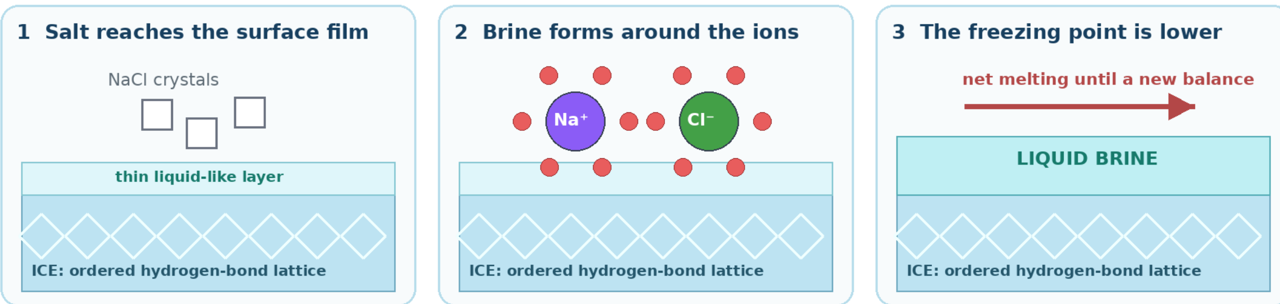


A useful visual summary from your collection.

BETTER WORDING Describe an increasingly open three-dimensional hydrogen-bond structure—not “incomplete chains.” The local arrangement is tetrahedral rather than a set of simple chains.

6 SALT ON ICE

Salt changes the equilibrium freezing temperature; it is not merely an obstacle delaying hydrogen-bond reconnection.



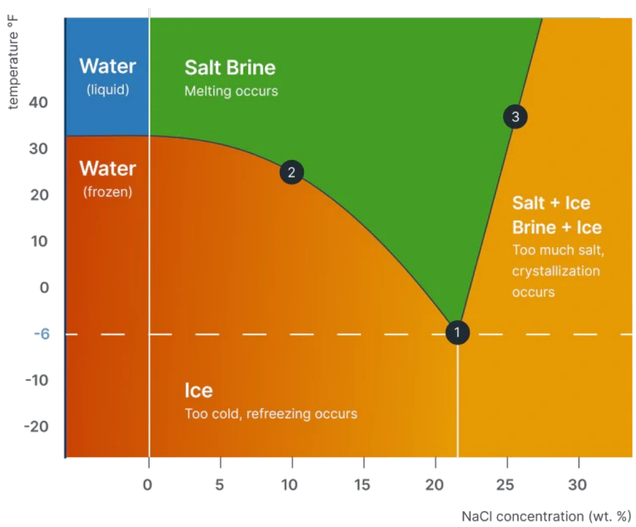
The clearest teaching sequence is surface film → hydrated ions → liquid brine and a new ice–liquid balance.

1 **A liquid-like surface is available.** The outermost ice surface can be disordered below 0°C. Salt dissolves there and in any meltwater present.

2 **NaCl separates into Na^+ and Cl^-.** Water molecules hydrate the ions. Dissolved particles lower liquid water's chemical potential—commonly described as lowering its freezing point.

3 **The balance shifts toward brine.** At a temperature where pure water would freeze, salty water can remain liquid. Ice melts until concentration and temperature reach a new equilibrium; melting absorbs heat.

4 **The equilibrium low-temperature limit is about −21.1°C (−6°F).** The NaCl–water eutectic is near 23.3% salt by mass. Below it, stable liquid brine is not expected; practical road-salt performance weakens well above that limit.



YOUR NaCl PHASE CHART • Point 1 marks the lowest equilibrium liquid-brine temperature.

Correct the earlier shortcut

Do not say salt leaves melting unchanged and only slows refreezing. Freezing and melting continue microscopically, but dissolved salt moves the equilibrium freezing temperature downward. The net result is additional melting.

Salt also does not mechanically wedge hydrogen bonds apart. Hydrated ions change the thermodynamics and structure of the liquid solution.

TEACHER'S CLOSING LINE **The same H_2O molecules occupy every phase; arrangement, motion, and hydrogen-bond organization determine which phase is stable.**

Sources: Laage & Hynes, Science (2006), doi:10.1126/science.1122154 • Shi et al., PCCP (2022), doi:10.1039/D2CP00752E • Bianco et al., J. Chem. Phys. (2022), doi:10.1063/5.0083371 • Song et al., Sci. Adv. (2026), doi:10.1126/sciadv.aec6748

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