

Liquids & Solids

CHEM 50 · Dr. Karmach

By the end of this unit, you can...

- Identify the intermolecular forces present in a substance and rank their relative strength
- Explain surface tension, viscosity, capillary action, and vapor pressure from the strength of intermolecular forces
- Relate intermolecular-force strength to boiling point and rank substances by boiling point
- Read a phase diagram: the stable phase at a given pressure and temperature, the triple and critical points, and the phase changes along a path
- Classify a solid as ionic, metallic, covalent network, or molecular, predict its properties, and count the atoms in a cubic unit cell

Today's route

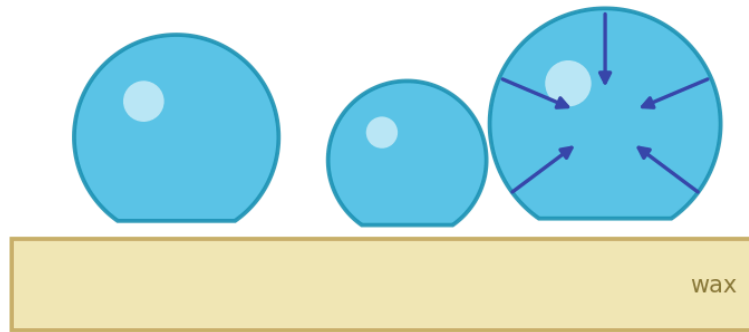
1. Intermolecular Forces
2. Properties of Liquids
3. IMFs & Boiling Point
4. Phase Diagrams
5. Types of Solids

1 • Intermolecular Forces

Identify which intermolecular forces a substance has and name the strongest one present, keeping these attractions between molecules distinct from the bonds inside them.

Why water beads and geckos climb

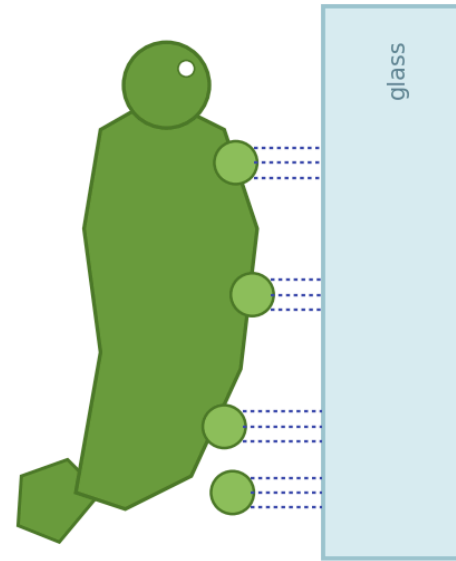
water on a waxed car



the water pulls itself into round beads

instead of spreading flat

a gecko on a glass wall

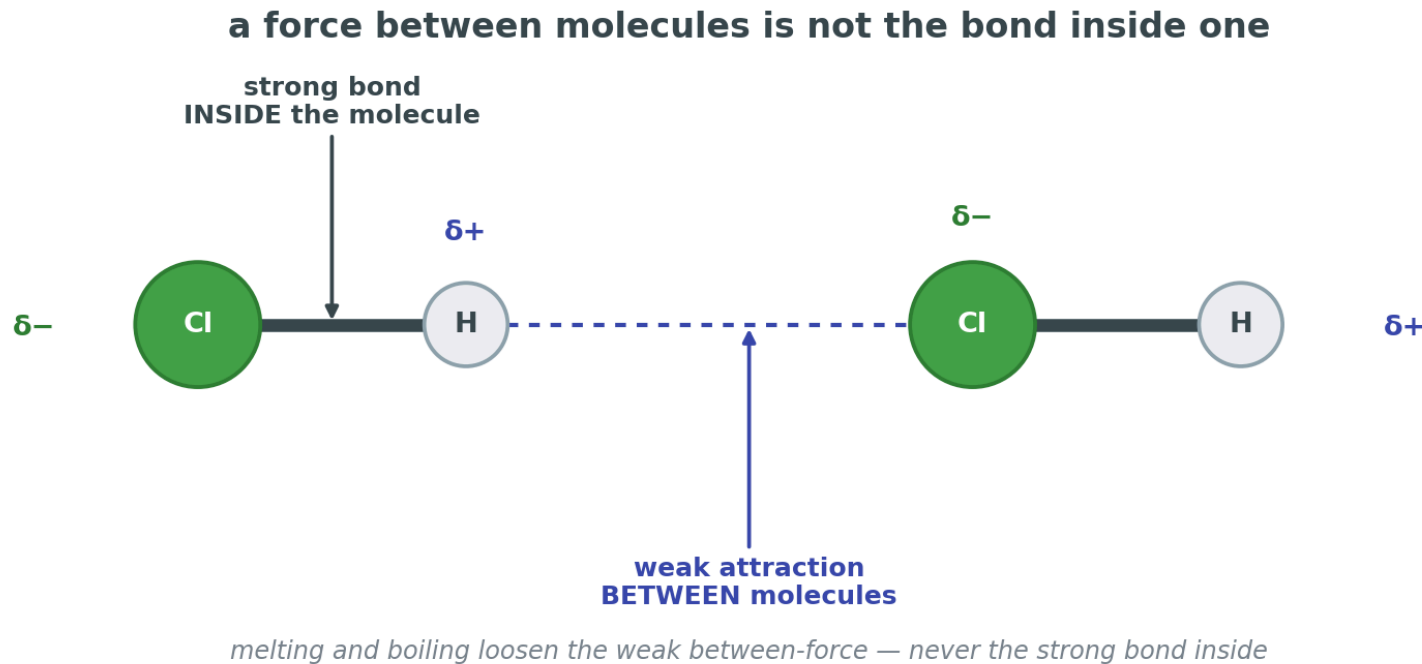


countless faint pulls hold its weight

each one tiny — together, enough

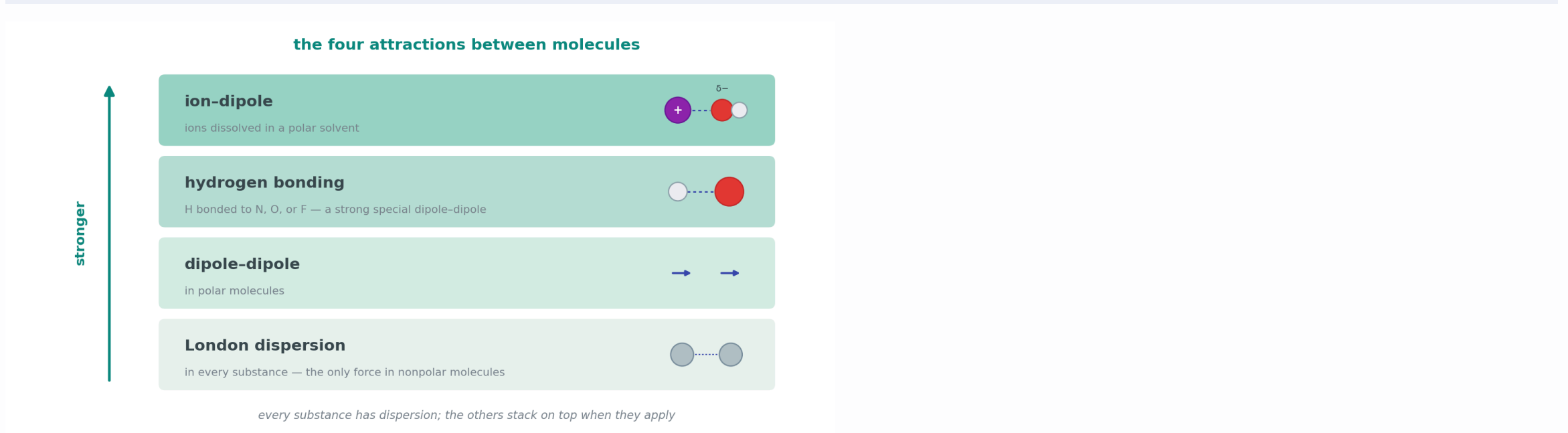
Water beads up on a waxed car. A gecko walks up a glass wall. Faint attractions between molecules, far weaker than the bonds inside them, hold and lift.

Forces between molecules, not the bonds within



An **intermolecular force** is an attraction between separate molecules. It is always weaker than the covalent bond holding one molecule together. Melting and boiling loosen these forces; the bonds inside stay intact.

The four kinds, weakest to strongest



Every substance has **London dispersion**. Polar molecules add **dipole-dipole**. An H on N, O, or F adds **hydrogen bonding**. Dissolved ions give **ion-dipole**, the strongest.

memory hook: I Hate Doing Laundry, strongest first
Ion-dipole > Hydrogen bonding > Dipole-dipole > London dispersion

Dispersion grows with size

London dispersion comes from the electron cloud shifting for an instant. A bigger, heavier cloud shifts more easily, so dispersion strengthens as molar mass rises. Among the nonpolar halogens, it climbs straight down the group.

$\text{F}_2 \cdot \text{Cl}_2 \cdot \text{Br}_2 \cdot \text{I}_2$: all nonpolar

molar mass 38.00 $\rightarrow$ 70.90 $\rightarrow$ 159.80 $\rightarrow$ 253.80 g/mol $\cdot$ dispersion rises with it



The method

1. **Identify the pieces.** Ions in a polar solvent, or molecules? Polar? Any H on N, O, or F?
2. **Name every force present.** Dispersion always; dipole-dipole if polar; hydrogen bonding if H-N/O/F; ion-dipole for dissolved ions.
3. **Pick the strongest.**



Worked example 1: methane

CH₄: carbon bonded to four hydrogens

tetrahedral · four identical C-H bonds · wanted: forces present, and the strongest

Natural gas is mostly methane. Name every intermolecular force it has, then the strongest.

✓ Worked example 1: solution

CH_4 : carbon bonded to four hydrogens
tetrahedral · four identical C-H bonds

Step 1 · Identify the pieces

Step 2 · Name every force present

nonpolar · no ionic pieces → **London dispersion only**

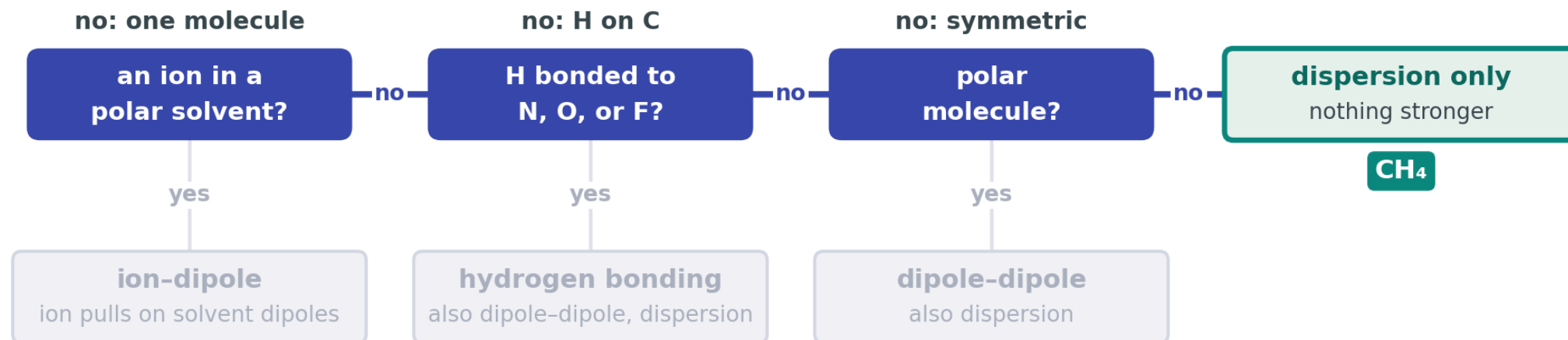
Step 3 · Pick the strongest

CH_4 → **strongest force: London dispersion**
the only force present, so it is also the strongest

 **Sense check:** A nonpolar molecule with no ions has just one option. Dispersion is the whole story for methane.

✓ Worked example 1: the route on the chart

CH₄: carbon bonded to four hydrogens
 found: London dispersion only · strongest: London dispersion



 **Sense check:** Three "no" answers run straight across to dispersion only. A symmetric molecule with every H on carbon has nothing stronger. ✓



Worked example 2: methanol

CH₃OH: an O-H group on a carbon
polar molecule · wanted: forces present, and the strongest

Methanol is the alcohol in some racing fuels. It is polar, so it has dipole-dipole attraction.

A common first answer: polar, so dipole-dipole is the strongest. Test it against the method.

✓ Worked example 2: forces present

CH_3OH : an O-H group on a carbon
polar molecule · the H sits directly on O

A common first answer

strongest force = dipole-dipole?

true for a polar molecule with no H on N, O, or F, but methanol has an O-H ✕

Step 1 · Identify the pieces

Step 2 · Name every force present

dispersion · dipole-dipole · hydrogen bonding (H on O) → **three forces present**

🧠 **Sense check:** Every molecule has dispersion. Polar adds dipole-dipole; the O-H adds hydrogen bonding on top.

✓ Worked example 2: the strongest force

CH_3OH : three forces present
dispersion · dipole-dipole · hydrogen bonding (H on O)

Step 3 · Pick the strongest

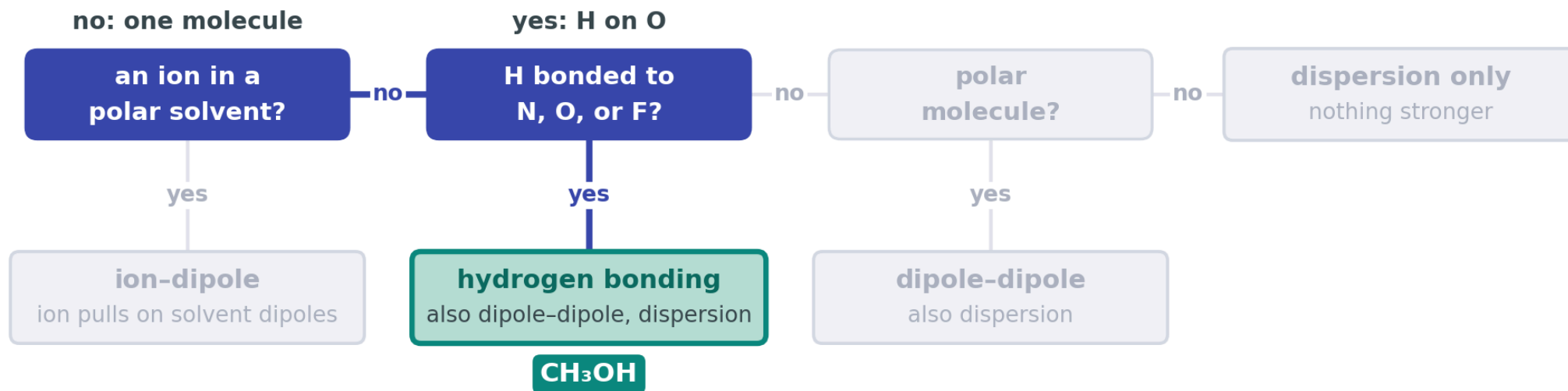
$\text{CH}_3\text{OH} \rightarrow$ strongest force: hydrogen bonding
H-O present · a strong special dipole-dipole, above ordinary dipole-dipole and dispersion

🧠 **Sense check:** An H on N, O, or F lifts the strongest force from dipole-dipole up to hydrogen bonding.

✓ Worked example 2: the route on the chart

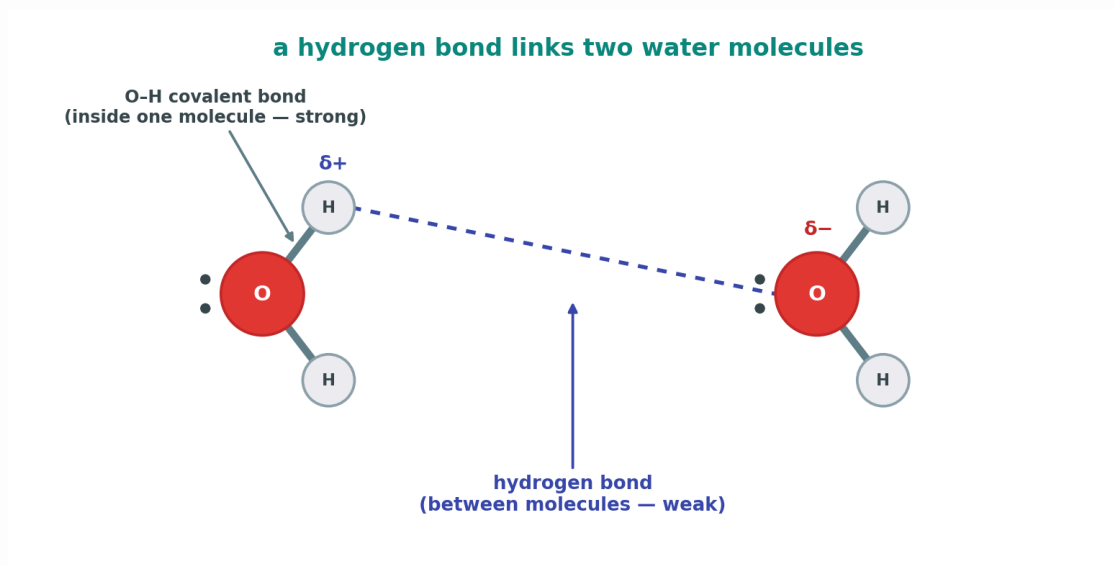
CH₃OH: an O-H group on a carbon

found: dispersion + dipole-dipole + hydrogen bonding · strongest: hydrogen bonding



 **Sense check:** The scan stops at the second question. An H on O exits at hydrogen bonding before polarity is ever asked. ✓

Take-home: hydrogen bonding needs H on N, O, or F



hydrogen bonding: H_2O · NH_3 · CH_3OH · none: CH_4 · CH_3OCH_3 · PH_3

memory hook: hydrogen bonding is FON · the H must sit directly on F, O, or N · an H on C, P, S, or Cl does not qualify

The dashed link, a hydrogen bond, joins one water's $\delta+$ hydrogen to a lone pair on the next molecule's $\delta-$ oxygen. It is far weaker than the covalent O-H.

Your turn: hydrogen sulfide

H₂S: bent, two S-H bonds
polar molecule · sulfur is not N, O, or F

step	H ₂ S
1 · identify the pieces	a molecule · polar · H bonded to _____
2 · name every force	dispersion, plus _____
3 · pick the strongest	_____

Fill the three cells. Watch the atom the H sits on.

H₂S → strongest force: dipole-dipole

H on sulfur, not N/O/F → no hydrogen bonding · dispersion + dipole-dipole, strongest is dipole-dipole

⚠ Where this goes wrong

Naming the covalent bond as the force between molecules. The bonds inside a molecule are intramolecular. They hold one molecule together and do not break when it melts or boils. Intermolecular forces act between molecules; melting and boiling loosen those.

Stopping at dipole-dipole when an H sits on N, O, or F. A polar molecule does have dipole-dipole. But an H bonded to nitrogen, oxygen, or fluorine upgrades the strongest force to hydrogen bonding, the stronger special case.

Defaulting to dispersion and missing the stronger force. Dispersion is in every molecule, but it is the weakest. Scan for an H on N, O, or F first, then for a dipole. The strongest present is the answer, not dispersion by default.

Ranking the forces in the wrong order. The order runs dispersion, dipole-dipole, hydrogen bonding, ion-dipole. Hydrogen bonding is not the strongest of all; ion-dipole outranks it.



Practice 1

hydrogen fluoride, HF

a polar molecule · the single H is bonded to fluorine

What is the strongest intermolecular force present in HF?

- A. London dispersion: every molecule has it, so it must be the strongest
- B. Ordinary dipole-dipole: HF is polar, so dipole-dipole is as strong as it gets
- C. Hydrogen bonding: the H is bonded directly to fluorine, one of N, O, F
- D. The H-F covalent bond: that is the force holding the molecule to its neighbours

✓ Practice 1 answer: C

HF → strongest force: hydrogen bonding · answer C

H bonded directly to F · a strong special dipole-dipole, the strongest force here

B stopped one rung early: HF is polar, but the H bonded to fluorine upgrades the strongest force to hydrogen bonding, above ordinary dipole-dipole. A defaulted to the weakest force; dispersion is in every molecule but never the strongest when a stronger one is present. D named the H-F bond inside the molecule, which is intramolecular and does not act between molecules.

 **Sense check:** Scan from the top: an H on F means hydrogen bonding, and the scan stops there.



Worked example 3: ranking three molecules

propane C_3H_8 · dimethyl ether CH_3OCH_3 · ethanol $\text{C}_2\text{H}_5\text{OH}$
molar mass $\approx 44, 46, 46$ g/mol · wanted: rank by the strongest force each has

Three molecules of nearly equal molar mass. Rank them by the strength of the strongest intermolecular force in each, weakest first.

✓ Worked example 3: forces present

propane C_3H_8 · dimethyl ether CH_3OCH_3 · ethanol $\text{C}_2\text{H}_5\text{OH}$
molar mass $\approx 44, 46, 46$ g/mol · dispersion is comparable in all three

Step 1 · Identify the pieces

Step 2 · Name every force present

propane $\rightarrow$ dispersion · ether $\rightarrow$ + dipole-dipole · ethanol $\rightarrow$ + hydrogen bonding

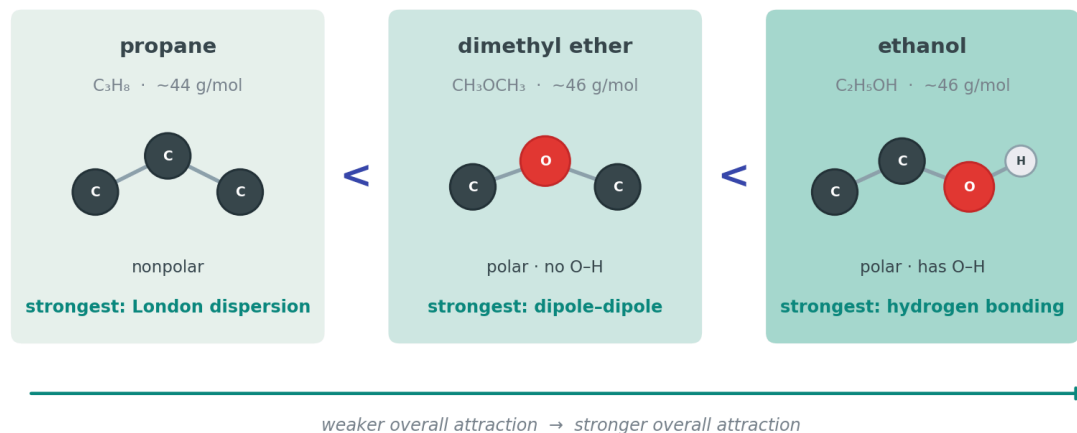
 **Sense check:** Each one has dispersion. The polar ether adds dipole-dipole; ethanol's O-H adds hydrogen bonding on top.

✓ Worked example 3: the ranking

propane · dimethyl ether · ethanol: same mass range
strongest force: dispersion < dipole-dipole < hydrogen bonding

Step 3 · Pick the strongest

same mass range — the strongest force decides the ranking

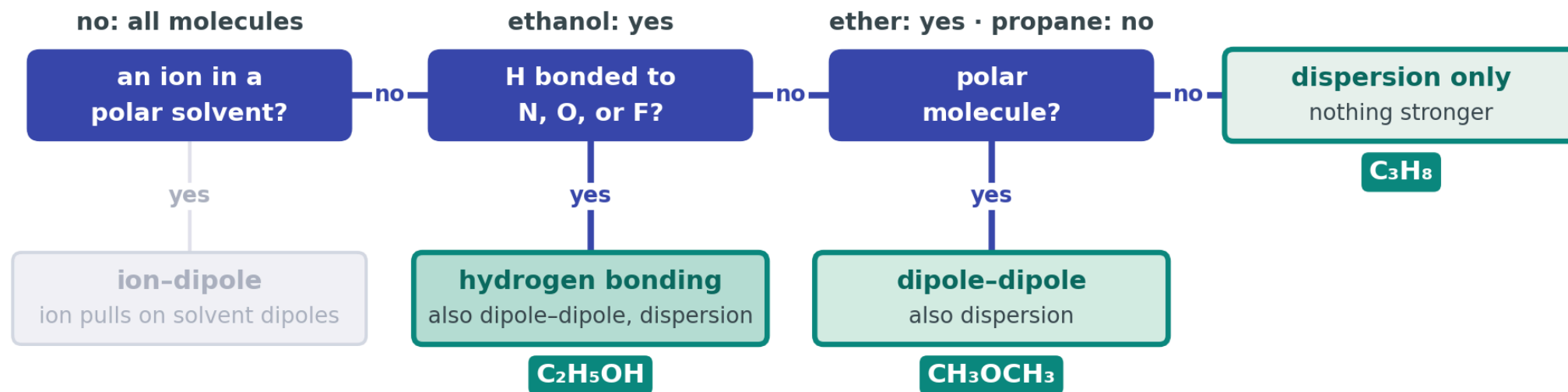


 **Sense check:** Similar masses, so the strongest-force type sets the order: propane < dimethyl ether < ethanol.

✓ Worked example 3: the route on the chart

propane C_3H_8 · dimethyl ether CH_3OCH_3 · ethanol $\text{C}_2\text{H}_5\text{OH}$

found: dispersion < dipole-dipole < hydrogen bonding



Sense check: Three molecules leave by three exits. Each exit names that molecule's strongest force, so the exits set the order: propane < dimethyl ether < ethanol. ✓



Practice 2

argon (Ar) · formaldehyde (CH_2O) · methylamine (CH_3NH_2) · Na^+ dissolved in water
 CH_2O and CH_3NH_2 are polar molecules · rank weakest first

Which ranking orders the four by the strength of the strongest intermolecular force each one has, weakest first?

- A. Na^+ in water < CH_3NH_2 < CH_2O < Ar
- B. Ar < CH_2O < Na^+ in water < CH_3NH_2
- C. Na^+ in water < CH_2O < CH_3NH_2 < Ar
- D. Ar < CH_2O < CH_3NH_2 < Na^+ in water

✓ Practice 2 answer: D

$\text{Ar} < \text{CH}_2\text{O} < \text{CH}_3\text{NH}_2 < \text{Na}^+$ in water · answer D
dispersion only · dipole-dipole · hydrogen bonding · ion-dipole

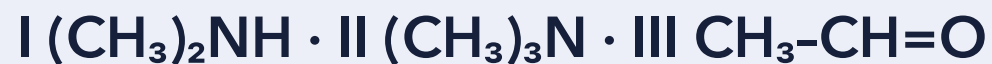
Argon is a lone nonpolar atom: dispersion only. CH_2O is polar, but both H atoms sit on carbon: dipole-dipole. CH_3NH_2 has H on N: hydrogen bonding. Na^+ pulls on water's dipoles: ion-dipole.

B put hydrogen bonding at the top; ion-dipole outranks it. C ranked by molar mass, $22.99 < 30.03 < 31.06 < 39.95$ g/mol, as if dispersion decided everything. A is the right order read strongest first.

 **Sense check:** Scan each one for a dissolved ion, then an H on N, O, or F, then polarity. The first test it passes names its strongest force.



Practice 3



dimethylamine · trimethylamine · acetaldehyde · all three are polar molecules

Which of the three can hydrogen bond with other molecules of its own kind?

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

✓ Practice 3 answer: A

only I, $(\text{CH}_3)_2\text{NH}$, has an H on N, O, or F · answer A

I: one H bonded to N · II: all nine H bonded to C · III: all four H bonded to C, none to O

B counted the N in $(\text{CH}_3)_3\text{N}$. Nitrogen is present, but all three of its bonds go to carbon, so no H sits on it. C counted the O in $\text{CH}_3\text{-CH=O}$. The H beside that O is bonded to carbon, not to oxygen. D treated every N or O atom as a hydrogen-bond trigger.

🧠 **Sense check:** An N, O, or F in the formula is not enough. The H must be bonded directly to it. ✓



Practice 4

glucose $\text{C}_6\text{H}_{12}\text{O}_6$ · potassium chloride KCl
each one dissolved in water · glucose carries five O-H groups

A sports drink holds dissolved glucose and dissolved KCl. What is the strongest attraction between each solute and the surrounding water?

- A. glucose: ion-dipole · KCl: ion-dipole
- B. glucose: hydrogen bonding · KCl: ion-dipole
- C. glucose: hydrogen bonding · KCl: hydrogen bonding
- D. glucose: dipole-dipole · KCl: ion-dipole

✓ Practice 4 answer: B

glucose: hydrogen bonding · KCl: ion-dipole · answer B

$\text{C}_6\text{H}_{12}\text{O}_6$ is molecular: dissolves as whole molecules · KCl is ionic: K^+ and Cl^- ions in water

A read every dissolved solute as ions. Glucose is a molecular compound, a nonelectrolyte: it dissolves as whole molecules, so it has no ion to pull on water. C put hydrogen bonding at the top of the scale; ion-dipole outranks it, and KCl releases ions. D stopped at dipole-dipole for glucose, but its O-H groups hydrogen bond with water.

 **Sense check:** The scan asks about ions first. KCl passes; glucose stays whole and exits at its O-H groups. ✓



Practice 5



neon · carbon tetrafluoride · fluoroform · ethylamine

Rank the four by how strongly their particles attract one another, weakest first.

- A. $\text{Ne} < \text{CH}_3\text{CH}_2\text{NH}_2 < \text{CHF}_3 < \text{CF}_4$
- B. $\text{Ne} < \text{CHF}_3 < \text{CF}_4 < \text{CH}_3\text{CH}_2\text{NH}_2$
- C. $\text{CH}_3\text{CH}_2\text{NH}_2 < \text{CHF}_3 < \text{CF}_4 < \text{Ne}$
- D. $\text{Ne} < \text{CF}_4 < \text{CHF}_3 < \text{CH}_3\text{CH}_2\text{NH}_2$
- E. $\text{Ne} < \text{CF}_4 < \text{CH}_3\text{CH}_2\text{NH}_2 < \text{CHF}_3$

✓ Practice 5 answer: D

Ne < CF₄ < CHF₃ < CH₃CH₂NH₂ · answer D

dispersion, small cloud · dispersion, larger cloud · dipole-dipole · hydrogen bonding

Tetrahedral CF₄ cancels its four C-F dipoles, so it has dispersion only, like Ne, but from a larger cloud. CHF₃ is polar with its H on carbon: dipole-dipole. CH₃CH₂NH₂ has H on N: hydrogen bonding.

A ranked by molar mass alone: 20.18 < 45.09 < 70.02 < 88.01 g/mol. B counted CF₄ as polar from its polar bonds, then let its larger mass beat CHF₃. C is the right order read strongest first. E counted the F in CHF₃ as a hydrogen-bond trigger, then ranked the two hydrogen bonders by size.

 **Sense check:** Force type sets the order; size only splits Ne from CF₄. Boiling points agree: Ne –246 °C, CF₄ –128 °C, CHF₃ –82 °C, CH₃CH₂NH₂ 17 °C. ✓



Check yourself

1. Acetone (CH_3COCH_3) is a polar molecule with no O-H, N-H, or F-H bond. Name every intermolecular force it has, then the strongest.
2. Two nonpolar gases differ only in size. Which has the stronger dispersion force, and why?

Stronger intermolecular forces hold a liquid together more tightly, so more heat is needed to boil it. Ranking these forces is the first step toward predicting which substance boils at the higher temperature.

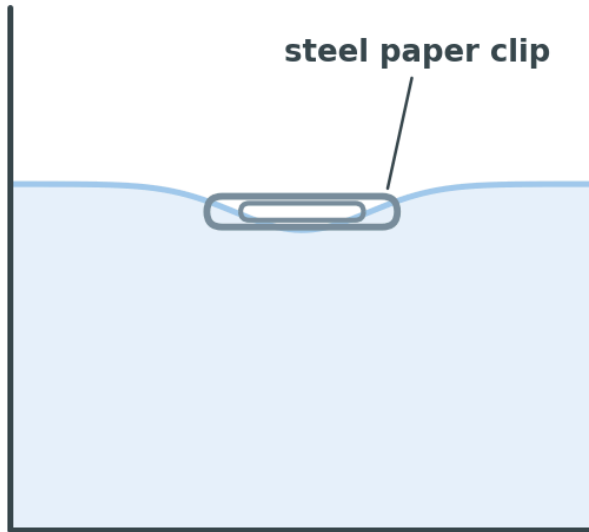
2 · Properties of Liquids

Explain surface tension, viscosity, capillary action, and vapor pressure from the strength of a liquid's intermolecular forces, and predict which of two liquids shows more of each.

A paper clip on water

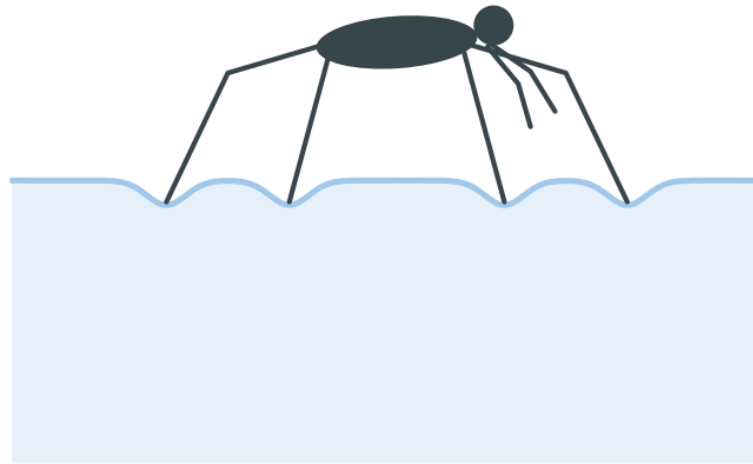
A liquid surface can carry weight

denser than water



the surface dips, but it does not let go

a water strider on a pond



each foot presses a dimple; none breaks through

Steel is denser than water, yet a paper clip can rest on a still surface. Insects stand on ponds the same way. The surface holds like a stretched skin.

Intermolecular forces set a liquid's behavior

The attractions between molecules control how a liquid acts: how its surface holds, how it flows, and how readily its molecules escape as vapor. Stronger attractions hold the molecules together more tightly.

stronger intermolecular forces → higher surface tension · higher viscosity · lower vapor pressure

one cause, three effects · hydrogen bonding > dipole-dipole > dispersion · dispersion grows with molecular size

memory hook: strong forces hold on

the holding properties rise (surface tension, viscosity) · the escaping one falls (vapor pressure)

Cohesion and adhesion

Cohesion is the attraction between molecules of the same liquid. **Adhesion** is the attraction between the liquid and a different material it touches. Behavior at any boundary follows from which attraction is stronger.

cohesion: liquid ↔ itself · adhesion: liquid ↔ another surface
a raindrop holds together: cohesion · water wets clean glass: adhesion

Surface tension: an inward pull

A molecule inside the liquid is pulled equally in every direction. A surface molecule has neighbors only beside and below, so the net pull is inward. The tightened surface resists stretching.

stronger forces → tighter surface → higher surface tension

drops pull toward spheres, the shape with the least surface · a light object can rest on the tightened surface

Viscosity: resistance to flow

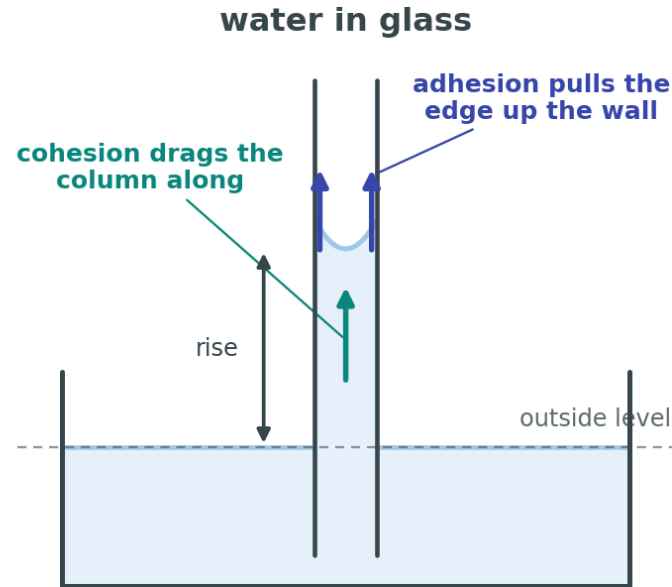
Flow makes molecules slide past their neighbors. Anything that holds neighbors together slows the slide: stronger forces, longer molecules with more contact, lower temperature.

viscosity rises with stronger forces · longer chains · lower temperature

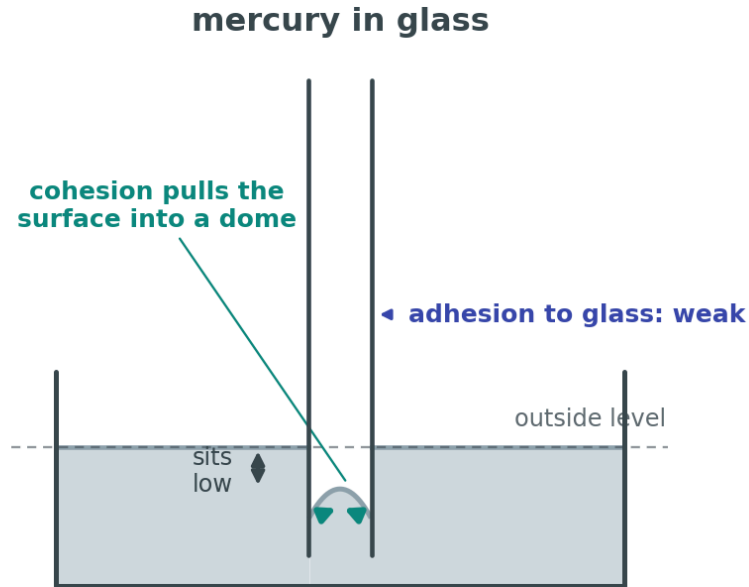
$\text{C}_5\text{H}_{12} < \text{C}_6\text{H}_{14} < \text{C}_7\text{H}_{16}$ in viscosity · warming a liquid always thins it

Capillary action and the meniscus

The stronger attraction sets the meniscus



adhesion beats cohesion: climbs, concave meniscus

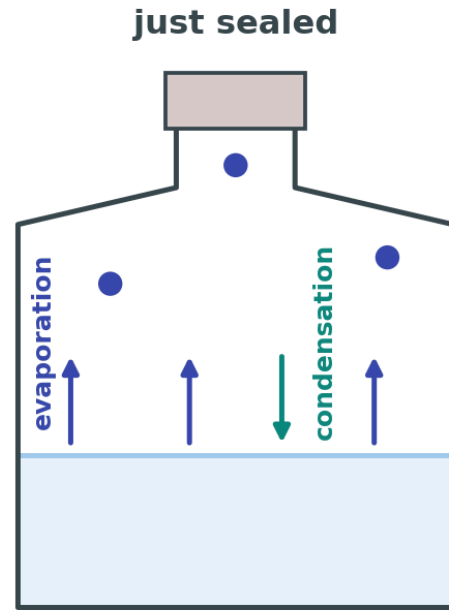


cohesion beats adhesion: stays low, convex meniscus

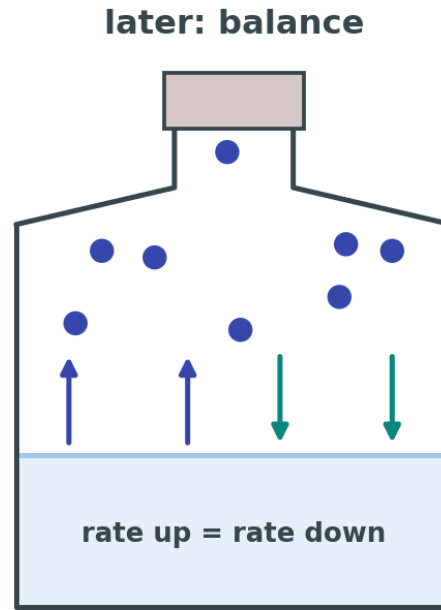
Adhesion pulls water up the glass wall and cohesion drags the column along: water climbs, surface dipping in the middle. Mercury coheres more than it adheres to glass: it bulges and stays low.

Vapor pressure: escape balanced by return

Vapor pressure: escape and return come to balance



evaporation outruns condensation: vapor builds



equal rates: the steady pressure = vapor pressure

In a sealed flask, evaporation and condensation soon run at equal rates and the vapor's pressure holds steady: the vapor pressure. Stronger forces let fewer molecules escape, so it sits lower.



The method

1. **Identify each liquid's strongest force.** Hydrogen bonding, dipole-dipole, or dispersion; same type, then size decides.
2. **Name what the property measures.** Holding a surface, flowing, or escaping.
3. **Stronger forces hold tighter.** More surface tension, more viscosity, less vapor.



Worked example 1: viscosity of two liquids

hexane (C_6H_{14}) vs 1-pentanol ($\text{C}_5\text{H}_{11}\text{OH}$)

86.17 g/mol · 88.15 g/mol · nearly equal size · wanted: the more viscous liquid

Two clear liquids of nearly the same molar mass. One pours like water; the other pours like a light oil.

Name the more viscous liquid, and the force that explains it.

✓ Worked example 1: solution

hexane (C_6H_{14}) vs 1-pentanol ($\text{C}_5\text{H}_{11}\text{OH}$)
86.17 g/mol · 88.15 g/mol · nearly equal size

Step 1 · Identify each liquid's strongest force

Step 2 · Name what the property measures

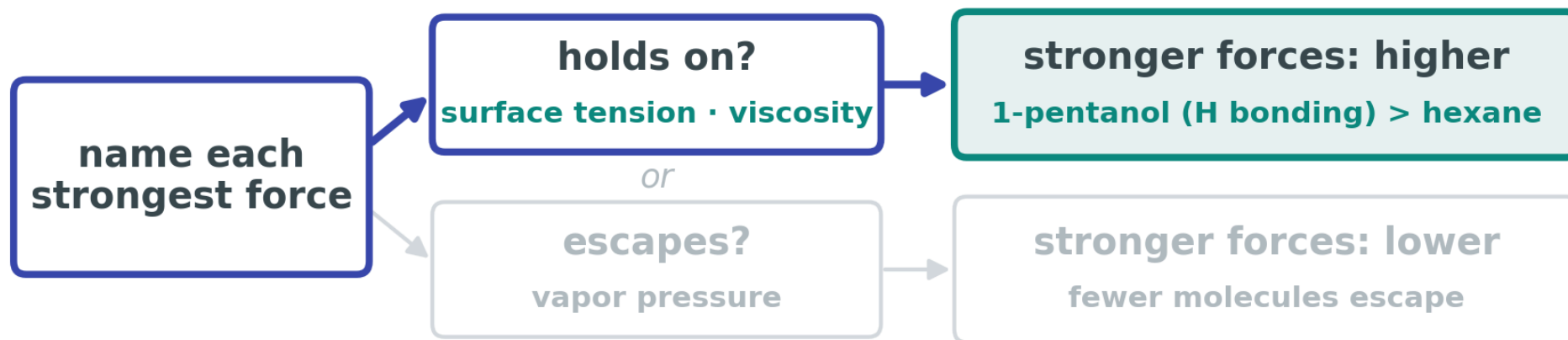
Step 3 · Stronger forces hold tighter

1-pentanol: hydrogen bonding vs hexane: dispersion → **1-pentanol is more viscous**

🧠 **Sense check:** Near room temperature 1-pentanol is about twelve times as viscous as hexane, at nearly the same molar mass. The hydrogen bonds make the difference. ✓

✓ Worked example 1: the route on the strip

hexane (C_6H_{14}) vs 1-pentanol ($\text{C}_5\text{H}_{11}\text{OH}$)
viscosity measures holding on · found: 1-pentanol is more viscous



🧠 **Sense check:** A holding property rises with the stronger force. Hydrogen bonding beats dispersion, so 1-pentanol flows more slowly. ✓



Worked example 2: vapor pressure in sealed flasks

diethyl ether ($\text{C}_2\text{H}_5\text{OC}_2\text{H}_5$) vs water (H_2O), sealed flasks at $20\text{ }^\circ\text{C}$

74.12 g/mol · 18.02 g/mol · wanted: the higher vapor pressure

Neither flask is anywhere near boiling.

A common first answer: neither shows a vapor pressure, because neither liquid is boiling.

Name the liquid with the higher vapor pressure.

✓ Worked example 2: solution

diethyl ether ($\text{C}_2\text{H}_5\text{OC}_2\text{H}_5$) vs water (H_2O), sealed flasks at 20 °C
74.12 g/mol · 18.02 g/mol

The common first answer, tested

Step 1 · Identify each liquid's strongest force

Step 2 · Name what the property measures

Step 3 · Stronger forces hold tighter

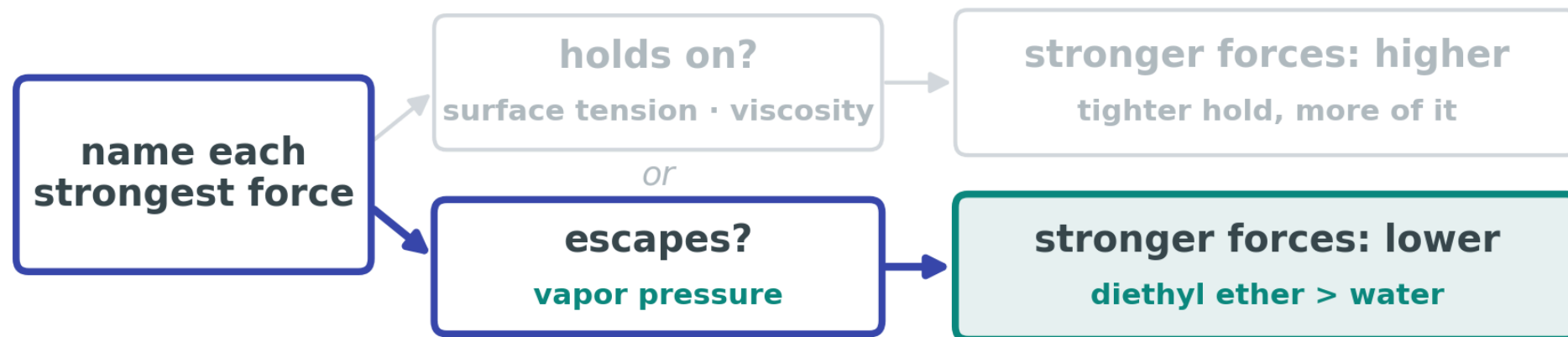
ether: weaker forces → more molecules escape

→ **diethyl ether has the higher vapor pressure**

🧠 **Sense check:** At 20 °C, ether's vapor pressure is about 25 times water's: 442 torr against 17.5 torr. Weak forces, easy escape, high vapor pressure. ✓

✓ Worked example 2: the route on the strip

diethyl ether ($\text{C}_2\text{H}_5\text{OC}_2\text{H}_5$) vs water (H_2O), sealed flasks at 20 °C
vapor pressure measures escape · found: diethyl ether has the higher vapor pressure



🧠 **Sense check:** An escaping property falls with the stronger force. Water's hydrogen bonds hold its molecules back, so ether's vapor pressure is the higher one. ✓

Take-home: every liquid has a vapor pressure

Boiling is not required. Above any liquid in a closed space, escape and return balance at a steady vapor pressure. Warmer liquid, more molecules with escape energy, higher vapor pressure.

any liquid, any temperature → some vapor pressure

higher temperature → higher vapor pressure · stronger forces → lower vapor pressure at the same temperature

🧩 Your turn: surface tension

water (H₂O) vs acetone (CH₃COCH₃)

18.02 g/mol · 58.08 g/mol · wanted: the higher surface tension

step	comparison
1 · strongest force	water: _____ · acetone: _____
2 · what the property measures	resistance to stretching the _____
3 · stronger forces hold tighter	higher surface tension: _____

water → higher surface tension

water: hydrogen bonding · acetone: dipole-dipole (no O-H) · water's surface pulls inward roughly three times harder

🧠 **Sense check:** Force type outranks size: water's hydrogen bonds tighten its surface far more than acetone's dipoles can. ✓

⚠ Where this goes wrong

Treating viscosity as density. Motor oil floats on water: it is less dense. Yet oil pours far more slowly: it is more viscous. Density is mass per volume; viscosity is resistance to flow. A liquid can be light and thick at the same time.

Waiting for boiling before vapor pressure. Every liquid has a vapor pressure at every temperature; a sealed bottle of water on a shelf holds vapor at its steady pressure. Boiling is the special temperature where the vapor pressure climbs to match the pressure outside.

Making stronger forces raise everything. Stronger forces raise surface tension and viscosity but lower vapor pressure. The first two measure how well molecules hold on; vapor pressure measures how easily they escape. One cause, opposite directions.

Expecting every liquid to curve like water. The meniscus reports a contest. Adhesion to glass beats cohesion in water: concave, and the liquid climbs. Cohesion beats adhesion in mercury: convex, and the level sits low.



Practice 1

an unknown liquid in a clean, narrow glass tube
the surface bulges upward (convex) · the level in the tube sits below the level outside

A clean glass capillary tube is dipped into a liquid. The liquid's surface bulges upward, and it does not climb. What does this show?

- A. Cohesion within the liquid is stronger than its adhesion to the glass
- B. Adhesion to the glass is stronger than cohesion within the liquid
- C. The glass repels the liquid, pushing its surface into a dome
- D. The liquid has no intermolecular forces, so nothing pulls it up the wall

✓ Practice 1 answer: A

convex meniscus, no climb $\rightarrow$ cohesion $>$ adhesion · answer A
the liquid's own attractions beat its attraction to the wall · mercury in glass behaves this way

B describes water: when adhesion wins, the edge is dragged up the wall, giving a concave dip and a climbing column. C invents a repulsion; glass attracts every liquid at least weakly, and the dome comes from the liquid's own inward pull. D cannot happen: every substance has at least dispersion forces.

 **Sense check:** A dip in the middle means adhesion leads; a bulge means cohesion leads. The shape reads out the force balance directly.



Practice 2

1-propanol ($\text{C}_3\text{H}_7\text{OH}$) · acetone (CH_3COCH_3) · pentane (C_5H_{12}), sealed flasks at $20\text{ }^\circ\text{C}$
60.09 g/mol · 58.08 g/mol · 72.15 g/mol

Rank the three liquids from lowest to highest vapor pressure.

- A. pentane < acetone < 1-propanol
- B. 1-propanol < acetone < pentane
- C. pentane < 1-propanol < acetone
- D. 1-propanol < pentane < acetone

✓ Practice 2 answer: B

1-propanol < acetone < pentane · answer B

hydrogen bonding · dipole-dipole · dispersion only · weaker forces, more escape

The masses sit close, so force type decides. 1-Propanol's O-H hydrogen bonds. Acetone is polar with no O-H. Pentane is nonpolar. Vapor pressure measures escape, so it rises as the forces weaken.

A ranked the attractions, not the vapor pressure; stronger forces lower it. C ranked by molar mass alone, but pentane's extra mass cannot outpull a dipole or a hydrogen bond. D read acetone as nonpolar; its C=O makes it polar, so it holds on harder than pentane.

 **Sense check:** Strong forces hold, weak forces let go. Vapor pressure climbs from the hydrogen-bonded liquid to the dispersion-only one.



Practice 3

1-butanol ($\text{C}_4\text{H}_9\text{OH}$) vs diethyl ether ($\text{C}_2\text{H}_5\text{OC}_2\text{H}_5$), both at 20 °C
both $\text{C}_4\text{H}_{10}\text{O}$ · 74.12 g/mol

The two liquids share one formula. Compared with diethyl ether, what does 1-butanol show?

- A. Higher surface tension, viscosity and vapor pressure
- B. Lower surface tension and viscosity, higher vapor pressure
- C. Higher surface tension and viscosity, lower vapor pressure
- D. The same values: same formula, same molar mass

✓ Practice 3 answer: C

1-butanol: higher surface tension and viscosity, lower vapor pressure · answer C
both $C_4H_{10}O$: equal dispersion · 1-butanol: O-H, hydrogen bonding · ether: no H on O, dipole-dipole

Same formula, same size: the force type decides. Hydrogen bonding holds 1-butanol tighter, so the holding properties rise and the escaping one falls.

A raised all three; stronger forces lower vapor pressure. B reversed the ranking; hydrogen bonding outranks dipole-dipole. D let the shared formula decide, or counted the ether's O as hydrogen bonding; that needs an H on the O.

 **Sense check:** One O-H separates two liquids of identical size, and all three properties follow it. ✓



Practice 4

octane (C_8H_{18}) · ethanol ($\text{C}_2\text{H}_5\text{OH}$) · ethylene glycol ($\text{HOCH}_2\text{CH}_2\text{OH}$), all at 25 °C
114.22 g/mol · 46.07 g/mol · 62.07 g/mol

Order the three liquids from least viscous to most viscous.

- A. ethanol < ethylene glycol < octane
- B. ethylene glycol < ethanol < octane
- C. ethanol < octane < ethylene glycol
- D. octane < ethanol < ethylene glycol

✓ Practice 4 answer: D

octane < ethanol < ethylene glycol · answer D

dispersion only · one O-H per molecule · two O-H per molecule · stronger hold, slower flow

Octane is the heaviest, but it holds only by dispersion. Ethanol and ethylene glycol both hydrogen bond, so size decides: glycol is the larger molecule, 62.07 g/mol to 46.07, and carries two O-H per molecule, so it holds tightest.

A ranked by molar mass alone: $46.07 < 62.07 < 114.22$. B ran viscosity the way vapor pressure runs; stronger forces raise viscosity. C let octane's size outrank ethanol's hydrogen bond.

 **Sense check:** Near 25 °C, ethylene glycol is about 15 times as viscous as ethanol, and octane flows about twice as easily as ethanol. ✓

Check yourself

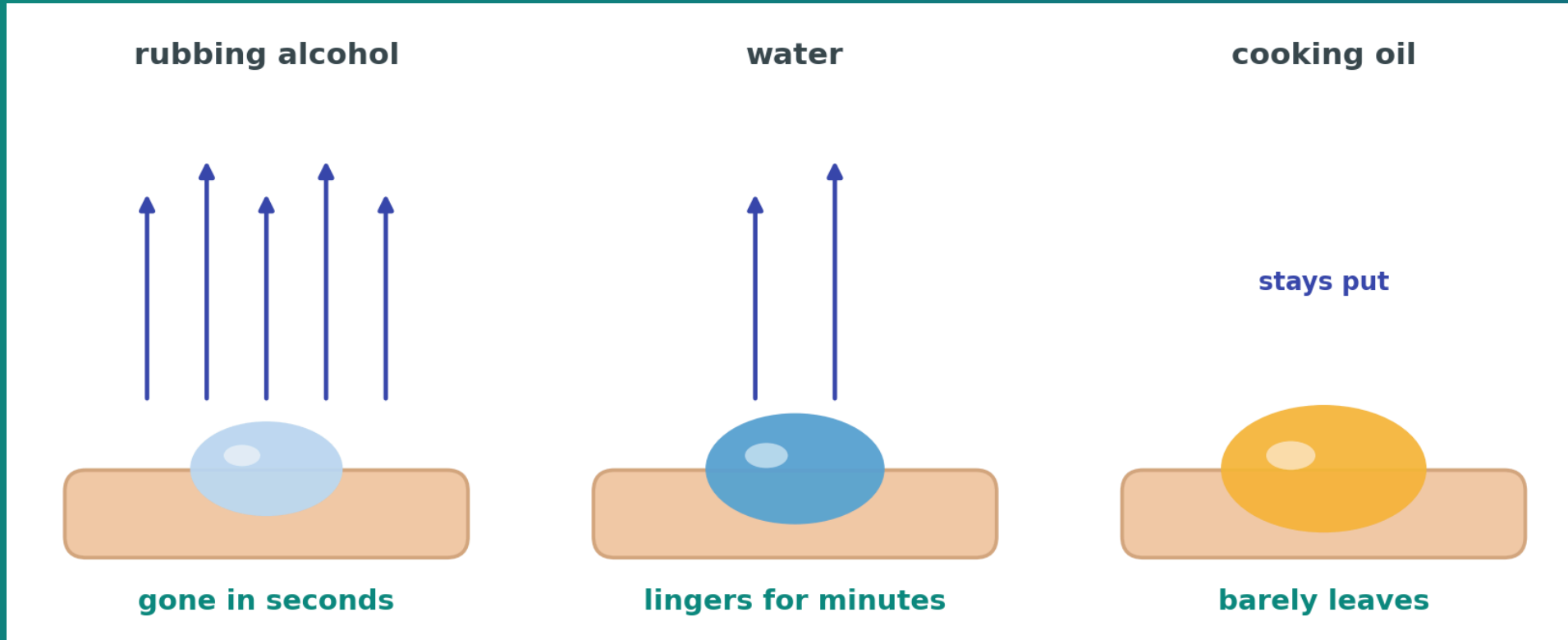
1. Glycerol's molecules each carry three O-H groups; acetone's carry none. Which liquid is more viscous at room temperature, and why?
2. A sealed flask of water sits at a steady vapor pressure. Name the two processes still running at the liquid surface and compare their rates.

A liquid boils when its vapor pressure climbs to meet the pressure above it. Stronger intermolecular forces mean a lower vapor pressure, so more heat is needed: ranking forces predicts which liquid boils higher.

3 · IMFs & Boiling Point

Predict which substance boils higher from its intermolecular forces: the stronger the attraction between molecules, the more energy needed to pull them apart, so the higher the boiling point; among nonpolar molecules the bigger one disperses more.

Three liquids off your skin

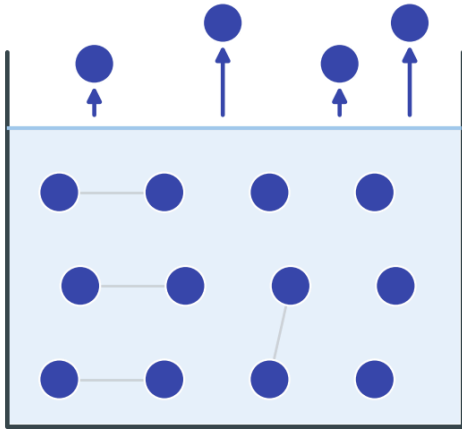


Rubbing alcohol dries in seconds. Water lingers for minutes. Cooking oil barely leaves at all. Stronger attractions between molecules hold a liquid together longer.

Boiling pulls molecules apart

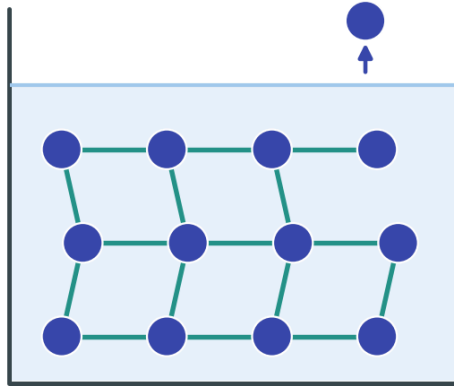
Boiling means pulling the molecules apart

weak attractions



molecules escape easily → low boiling point

strong attractions



more energy to separate → high boiling point

To boil, molecules must break free of their neighbors, and stronger attractions take more energy to overcome. The stronger the intermolecular forces, the higher the boiling point.

stronger intermolecular forces → higher boiling point

also raises melting point, surface tension, viscosity · lowers vapor pressure

Ranking the forces at equal size

When molecules are about the same size, the type of force sets the order. Hydrogen bonding pulls hardest, ordinary dipole-dipole attraction is weaker, and dispersion is weakest of the three.

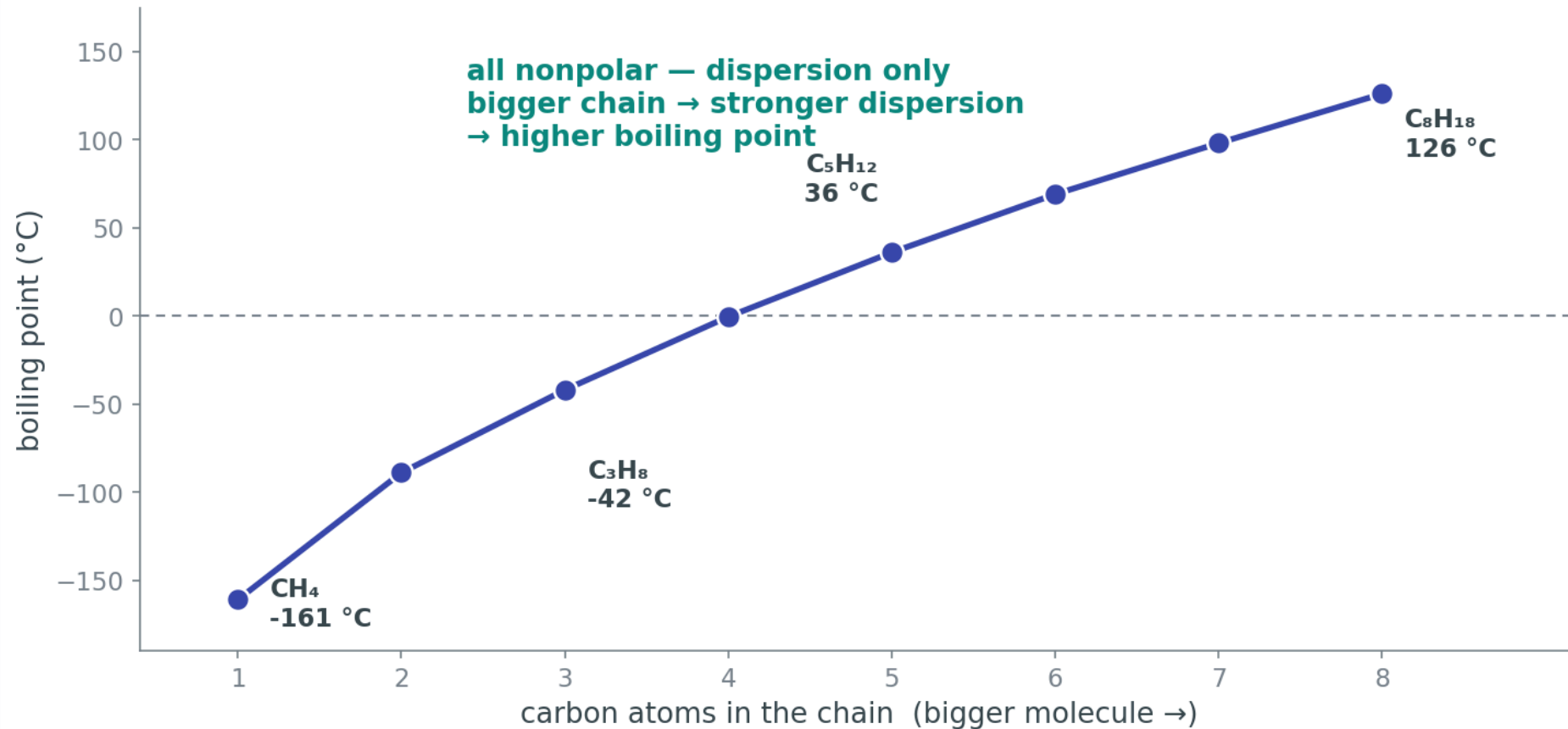
at $\approx 44\text{-}46$ g/mol: ethanol (hydrogen bonding) 78°C · dimethyl ether (dipole-dipole) -24°C · propane (dispersion) -42°C

nearly equal mass, so dispersion is nearly equal · the stronger force type boils higher

memory hook: type first, size breaks the tie

compare force types first · only within one type does the bigger molecule win

Bigger nonpolar molecules boil higher



Nonpolar molecules have only dispersion forces. Dispersion comes from the electrons, so a bigger molecule with more electrons and more surface attracts more strongly.



The method

1. **Identify each substance's strongest force.** Hydrogen bonding, dipole-dipole, or dispersion.
2. **The stronger force boils higher.** Across types, rank them: hydrogen bonding > dipole-dipole > dispersion.
3. **For a tie, the bigger molecule attracts more.** Same type: more electrons, more surface.



Worked example 1: same size, different force

dimethyl ether (CH_3OCH_3) vs ethanol ($\text{C}_2\text{H}_5\text{OH}$)

both $\text{C}_2\text{H}_6\text{O}$, molar mass 46.07 g/mol · wanted: which boils higher, and why

Two liquids built from the same atoms: the same molar mass, and nearly the same dispersion.

Name the higher-boiling liquid, and the force that explains it.

✓ Worked example 1: solution

dimethyl ether (CH_3OCH_3) vs ethanol ($\text{C}_2\text{H}_5\text{OH}$)

both $\text{C}_2\text{H}_6\text{O}$, 46.07 g/mol

Step 1 · Identify each substance's strongest force

Step 2 · The stronger force boils higher

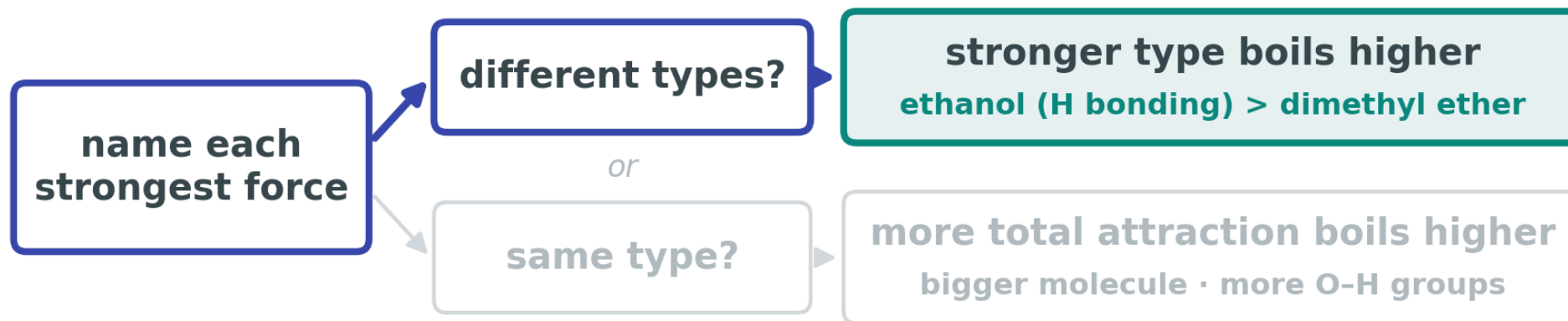
ethanol 78 °C · dimethyl ether –24 °C

hydrogen bonding vs dipole-dipole · same 46.07 g/mol

 **Sense check:** Identical mass, and hydrogen bonding lifts ethanol's boiling point 102 °C above dimethyl ether's. The force type, not the size, made the difference. ✓

✓ Worked example 1: the route on the map

dimethyl ether (CH_3OCH_3) vs ethanol ($\text{C}_2\text{H}_5\text{OH}$)
 given: both 46.07 g/mol · found: ethanol boils higher, 78 °C vs –24 °C



🧠 **Sense check:** Hydrogen bonding against dipole-dipole: two different types, so the top row settles it. ✓



Worked example 2: two halogens

chlorine (Cl_2) vs iodine (I_2)

Cl_2 70.90 g/mol · I_2 253.80 g/mol · both nonpolar · wanted: which boils higher, and why

A common first answer: both are nonpolar molecules with only dispersion forces, so they should boil at about the same temperature.

Name the higher-boiling halogen, and the reason.

✓ Worked example 2: solution

chlorine (Cl_2) vs iodine (I_2)

Cl_2 70.90 g/mol · I_2 253.80 g/mol · both nonpolar

Step 1 · Identify each substance's strongest force

Step 2 · The stronger force boils higher

Step 3 · For a tie, the bigger molecule attracts more

iodine 184 °C · chlorine –34 °C

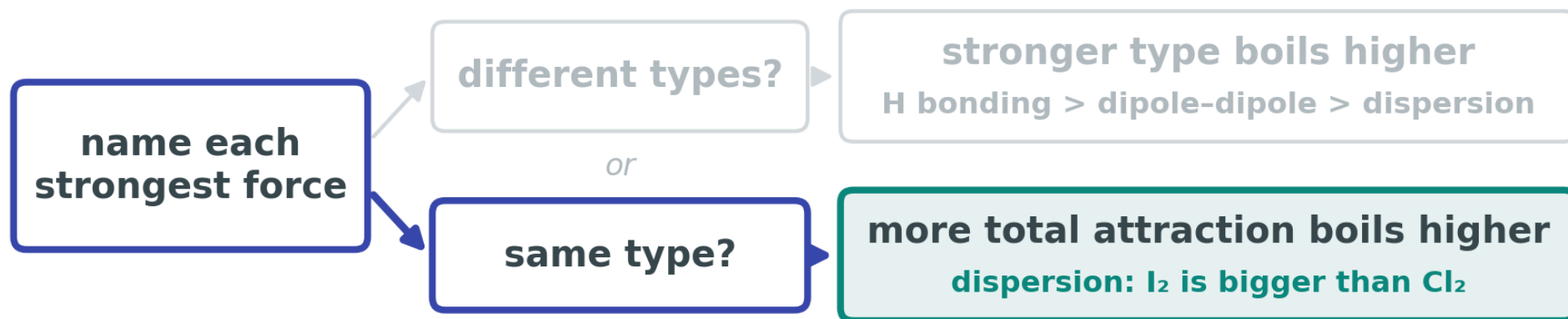
253.80 g/mol vs 70.90 g/mol · dispersion grows with size

🧠 **Sense check:** Iodine boils 218 °C above chlorine, and at room temperature iodine is a solid while chlorine is a gas. Same force type, very different strength. ✓

✓ Worked example 2: the route on the map

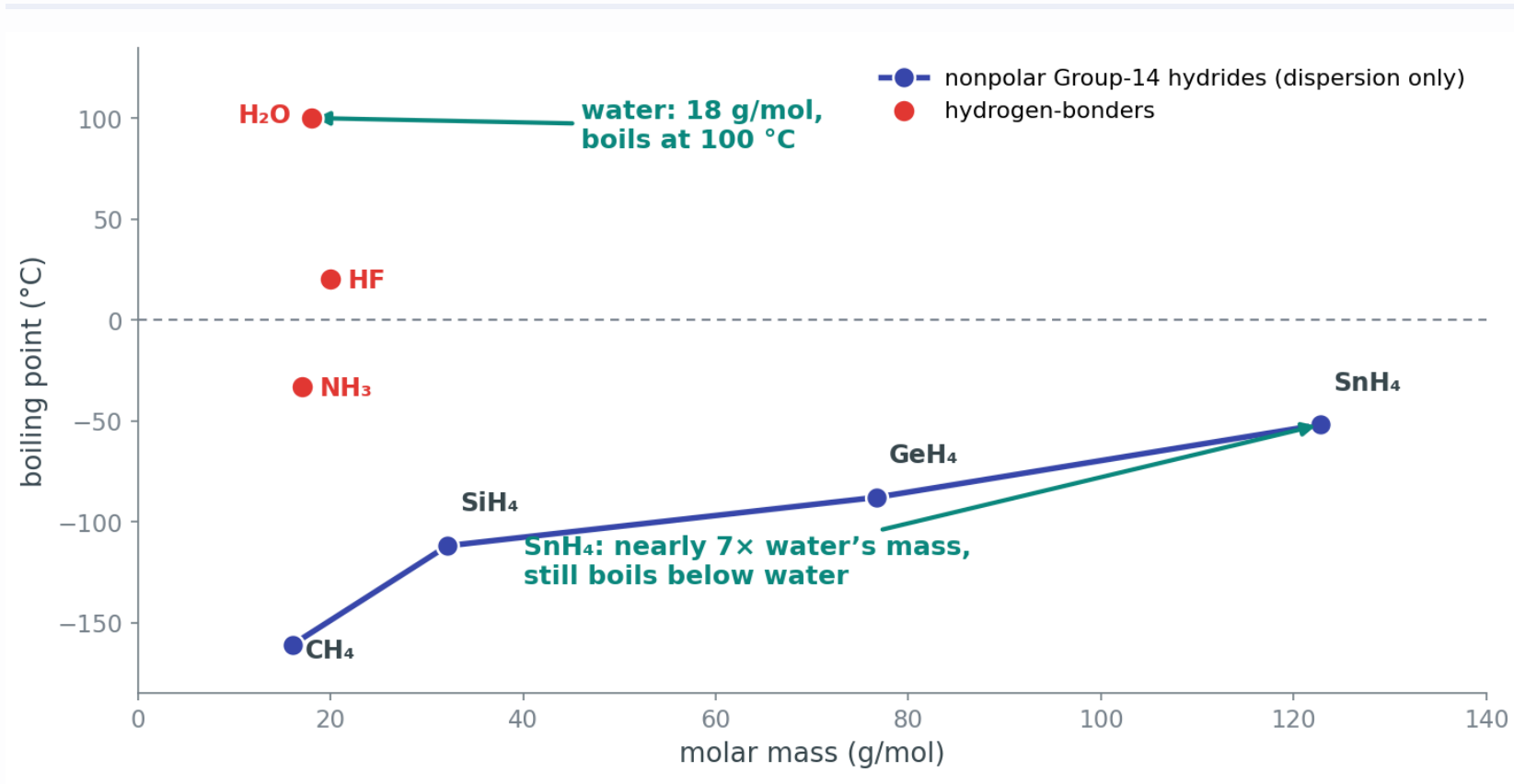
chlorine (Cl_2) vs iodine (I_2)

given: 70.90 vs 253.80 g/mol · found: iodine boils higher, 184 °C vs –34 °C



 **Sense check:** Both have only dispersion, a tie in type, so the bottom row settles it: the bigger molecule boils higher. ✓

Take-home: type outranks mass



Size decides only among one force type. Across types, the stronger force wins against a far heavier molecule. Tin hydride is nearly seven times water's mass, yet water boils higher because water hydrogen bonds.

Your turn: methanol and ethane

methanol (CH_3OH) 32.04 g/mol · ethane (C_2H_6) 30.07 g/mol
nearly equal mass, so dispersion is nearly equal

methanol: strongest force = _____ · ethane: strongest force = _____ · higher boiling point: _____

Fill each strongest force, then name the higher-boiling liquid.

methanol: **hydrogen bonding** (O-H) · ethane: **dispersion** (nonpolar) ·
higher boiling point: **methanol**

 **Sense check:** Equal mass, so dispersion ties. Methanol's O-H adds hydrogen bonding, and it boils at 65 °C against ethane's -89 °C, 154 °C higher. ✓

⚠ Where this goes wrong

Heavier always boils higher. Mass alone does not decide. Water, 18.02 g/mol, boils at 100 °C, above butane at 58.12 g/mol (−0.5 °C), because water hydrogen bonds while butane has only dispersion. Rank by force first; size counts only within one type.

Reversing the trend. "Lighter molecules move faster, so they need a higher temperature to boil." Weakly held molecules escape more easily, not less. Weak forces mean a low boiling point; strong forces mean a high one.

Confusing forces with bonds. "The bigger molecule boils higher because its covalent bonds are stronger." Boiling never breaks the covalent bonds inside a molecule. It overcomes the attractions between whole molecules, which are far weaker than bonds.

Same type, same boiling point. Two nonpolar molecules share the dispersion force but not its strength. Dispersion grows with size, so iodine (253.80 g/mol) boils far above chlorine (70.90 g/mol).



Practice 1

pentane (C_5H_{12}) vs heptane (C_7H_{16})

pentane 72.15 g/mol · heptane 100.20 g/mol · both nonpolar

Pentane and heptane are both nonpolar. Which boils at the higher temperature, and why?

- A. Heptane: it is the larger molecule, so its dispersion forces are stronger and take more energy to overcome.
- B. Heptane: its covalent bonds are stronger and must be broken for it to boil.
- C. Pentane: lighter molecules move faster, so a higher temperature is needed to boil them off.
- D. They boil at nearly the same temperature, since both are nonpolar and rely on the same force.

✓ Practice 1 answer: A

pentane (C_5H_{12}) vs heptane (C_7H_{16})

pentane 72.15 g/mol · heptane 100.20 g/mol · both nonpolar: dispersion only

Both are nonpolar, so dispersion is the only force. Heptane is the larger molecule, so its dispersion is stronger and it boils higher. Answer A.

B confused forces with bonds: boiling overcomes the attractions between molecules, never the covalent bonds inside them. C reversed the trend: weakly held light molecules escape more easily and boil lower, not higher. D forgot that the same force type can differ in strength, and dispersion grows with size.

🧠 **Sense check:** Heptane boils at 98 °C, pentane at 36 °C, 62 °C higher for the larger molecule. ✓



Worked example 3: rank three by boiling point

butane (C_4H_{10}) · acetone ($\text{C}_3\text{H}_6\text{O}$) · 1-propanol ($\text{C}_3\text{H}_8\text{O}$)

58.12 · 58.08 · 60.09 g/mol · nearly equal mass · wanted: order the boiling points

Three liquids of nearly equal molar mass, so dispersion is about the same for all three.

Rank the three boiling points from lowest to highest.

✓ Worked example 3: solution

butane (C_4H_{10}) · acetone ($\text{C}_3\text{H}_6\text{O}$) · 1-propanol ($\text{C}_3\text{H}_8\text{O}$)
 58.12 · 58.08 · 60.09 g/mol · nearly equal mass

Step 1 · Identify each substance's strongest force

Step 2 · The stronger force boils higher

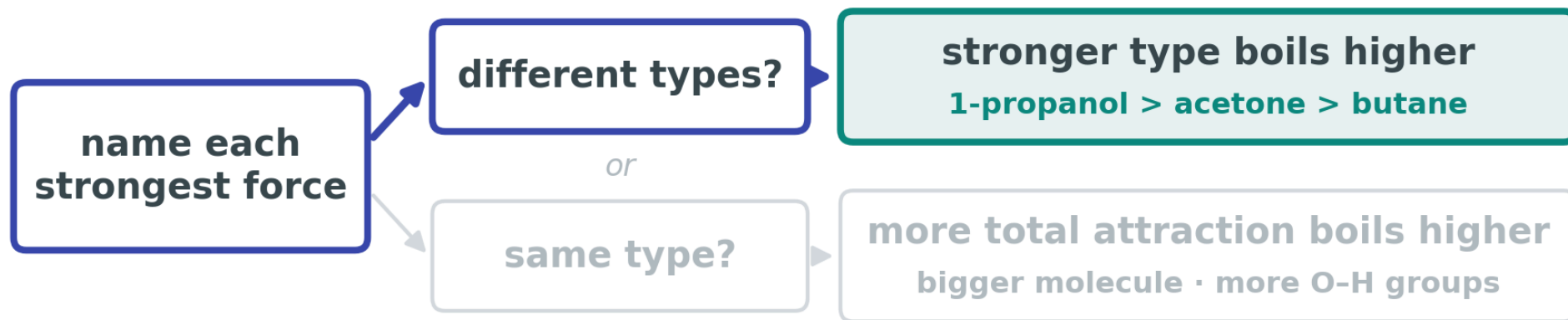
butane $-0.5\text{ }^{\circ}\text{C}$ · acetone $56\text{ }^{\circ}\text{C}$ · 1-propanol $97\text{ }^{\circ}\text{C}$
 dispersion < dipole-dipole < hydrogen bonding · masses within 2 g/mol

 **Sense check:** Lowest to highest: butane $-0.5\text{ }^{\circ}\text{C}$, acetone $56\text{ }^{\circ}\text{C}$, 1-propanol $97\text{ }^{\circ}\text{C}$. Propanol boils $41\text{ }^{\circ}\text{C}$ above acetone on hydrogen bonding alone, at nearly the same mass. ✓

✓ Worked example 3: the route on the map

butane (C_4H_{10}) · acetone ($\text{C}_3\text{H}_6\text{O}$) · 1-propanol ($\text{C}_3\text{H}_8\text{O}$)

given: 58.12 · 58.08 · 60.09 g/mol · found: butane $-0.5\text{ }^\circ\text{C}$ · acetone $56\text{ }^\circ\text{C}$ · 1-propanol $97\text{ }^\circ\text{C}$



🧠 **Sense check:** Three different types at nearly equal mass: the top row alone sets the whole order. ✓



Practice 2

neon (Ne) · krypton (Kr) · phosphine (PH_3) · ammonia (NH_3)
20.18 · 83.80 · 34.00 · 17.03 g/mol · PH_3 and NH_3 are polar molecules

Rank the four substances from lowest to highest boiling point.

- A. $\text{NH}_3 < \text{Ne} < \text{PH}_3 < \text{Kr}$
- B. $\text{Ne} < \text{Kr} < \text{NH}_3 < \text{PH}_3$
- C. $\text{Kr} < \text{Ne} < \text{PH}_3 < \text{NH}_3$
- D. $\text{Ne} < \text{Kr} < \text{PH}_3 < \text{NH}_3$

✓ Practice 2 answer: D

Ne < Kr < PH₃ < NH₃ · answer D

dispersion · dispersion, larger atom · dipole-dipole · hydrogen bonding

Neon and krypton are nonpolar atoms: dispersion only, and the larger krypton attracts more. PH₃ is polar, but its H sits on P: dipole-dipole. NH₃ has H on N: hydrogen bonding.

A ranked by mass alone; krypton is the heaviest, yet it has only dispersion. B let PH₃ hydrogen bond, but an H on P does not qualify. C reversed the size tie; the bigger atom disperses more and boils higher.

🧠 **Sense check:** Measured: Ne –246 °C, Kr –153 °C, PH₃ –88 °C, NH₃ –33 °C. Type first, then size breaks the tie. ✓



Practice 3

xenon (Xe) · methanethiol (CH_3SH) · formic acid (HCOOH) · fluoroethane ($\text{CH}_3\text{CH}_2\text{F}$)
131.29 · 48.10 · 46.03 · 48.06 g/mol · CH_3SH , HCOOH and $\text{CH}_3\text{CH}_2\text{F}$ are polar molecules

Which of the four has the highest boiling point?

- A. Xe
- B. CH_3SH
- C. HCOOH
- D. $\text{CH}_3\text{CH}_2\text{F}$

✓ Practice 3 answer: C

HCOOH: hydrogen bonding · answer C

Xe dispersion · CH₃SH dipole-dipole · HCOOH hydrogen bonding · CH₃CH₂F dipole-dipole

Only HCOOH has an H bonded to N, O, or F. Its last H sits on O, an O-H group, so it hydrogen bonds, the strongest type in the set.

A ranked by mass alone; xenon is by far the heaviest, but it is a nonpolar atom: dispersion only. B let sulfur qualify because it sits below oxygen; an H on S gives only dipole-dipole. D saw H and F in one molecule, but every H sits on C, not on F.

 **Sense check:** Measured: Xe –108 °C, CH₃CH₂F –38 °C, CH₃SH 6 °C, HCOOH 101 °C. The lightest of the four boils 95 °C above the next highest. ✓



Practice 4

ethanol ($\text{C}_2\text{H}_5\text{OH}$) vs dichloromethane (CH_2Cl_2), sealed flasks at $20\text{ }^\circ\text{C}$

$46.07\text{ g/mol} \cdot 84.93\text{ g/mol} \cdot \text{both polar molecules}$

Which liquid has the higher vapor pressure, and why?

- A. Ethanol: its lighter molecules move faster and escape more easily
- B. Ethanol: its hydrogen bonds push more molecules into the vapor
- C. They match: both are polar, so one force type holds each
- D. Dichloromethane: with no H on N, O, or F, it is held more weakly

✓ Practice 4 answer: D

ethanol: hydrogen bonding · dichloromethane: dipole-dipole · answer D
weaker attraction → more molecules escape → higher vapor pressure · 46.07 vs 84.93 g/mol

Ethanol's H sits on O, so it hydrogen bonds. Dichloromethane's H atoms sit on C, so it stops at dipole-dipole. The more weakly held liquid sends more molecules into the vapor.

A ranked by speed; vapor pressure follows how tightly the molecules are held, not how heavy they are. B reversed the trend: stronger attractions keep molecules in the liquid and lower the vapor pressure. C stopped at polar; ethanol's O-H adds hydrogen bonding on top.

 **Sense check:** Dichloromethane boils at 40 °C, 38 °C below ethanol's 78 °C. A low boiling point and a high vapor pressure both mark weak forces. ✓

 Practice 5

argon 39.95 · chloromethane 50.48 · bromomethane 94.93 · hydrogen peroxide 34.02 g/mol

Rank the four from lowest to highest boiling point.

- A. $\text{H}_2\text{O}_2 < \text{Ar} < \text{CH}_3\text{Cl} < \text{CH}_3\text{Br}$
- B. $\text{Ar} < \text{CH}_3\text{Cl} < \text{CH}_3\text{Br} < \text{H}_2\text{O}_2$
- C. $\text{Ar} < \text{CH}_3\text{Br} < \text{CH}_3\text{Cl} < \text{H}_2\text{O}_2$
- D. $\text{H}_2\text{O}_2 < \text{CH}_3\text{Br} < \text{CH}_3\text{Cl} < \text{Ar}$
- E. $\text{Ar} < \text{H}_2\text{O}_2 < \text{CH}_3\text{Cl} < \text{CH}_3\text{Br}$

✓ Practice 5 answer: B

Ar < CH₃Cl < CH₃Br < H₂O₂ · answer B

dispersion · dipole-dipole · dipole-dipole, larger molecule · hydrogen bonding

Argon is a nonpolar atom: dispersion only. CH₃Cl and CH₃Br have H on C: dipole-dipole, a tie in type, so the larger CH₃Br boils higher. H₂O₂ has H on O: hydrogen bonding.

A ranked by mass alone; H₂O₂ is the lightest, yet it has the strongest force. C let electronegativity break the tie; Cl pulls harder than Br, but within one type the bigger molecule wins. D is the right order read highest first. E missed the two O-H bonds in H₂O₂ and ranked it as a small dipole-dipole molecule.

 **Sense check:** Measured: Ar –186 °C, CH₃Cl –24 °C, CH₃Br 4 °C, H₂O₂ 150 °C. CH₃Br boils 28 °C above CH₃Cl. Type first, then size breaks the tie. ✓

Check yourself

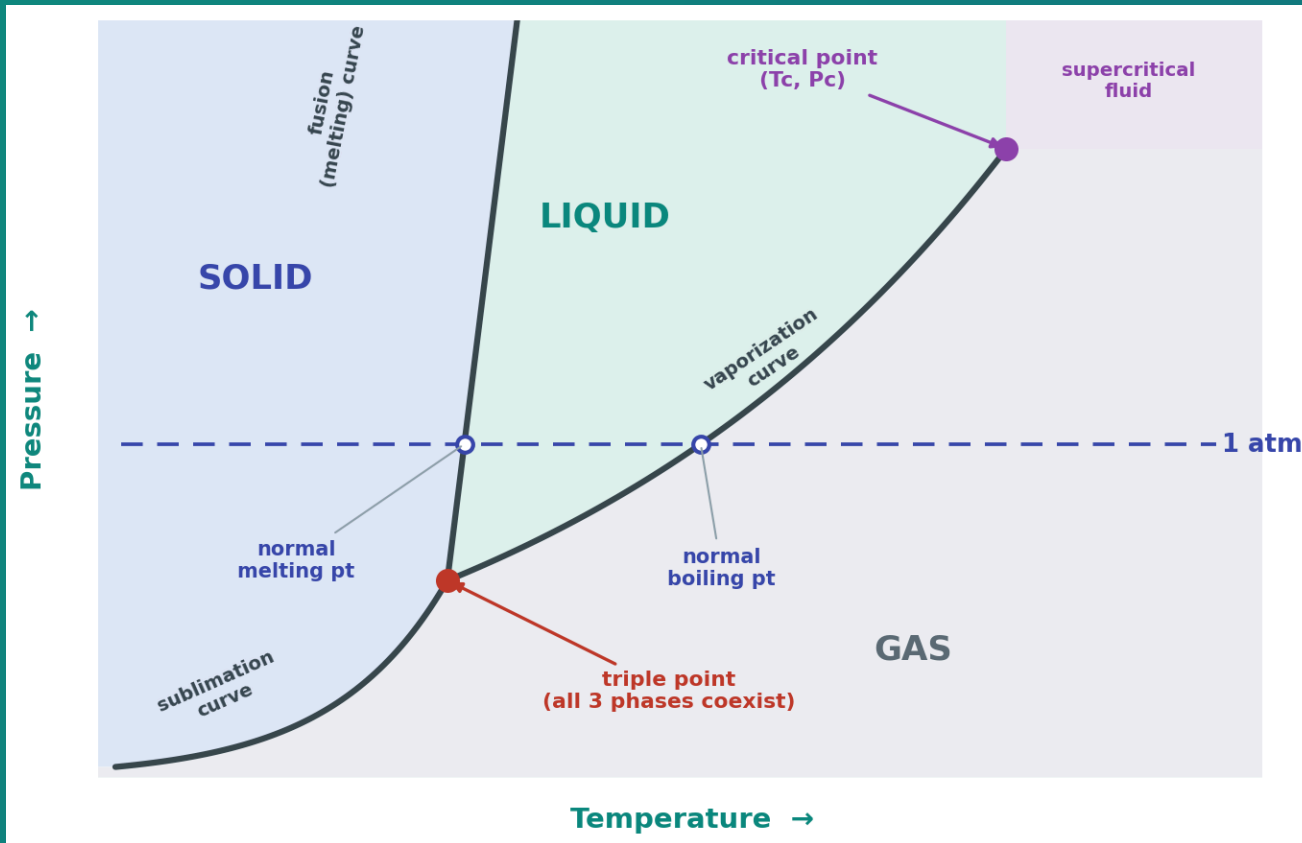
1. Neon and argon are both nonpolar. Which boils at the higher temperature, and which force decides it?
2. Dimethyl ether and ethanol have the same molar mass. Which boils higher, and why?

The strength ranking you just built predicts which substances give up their liquid state easily and which hold on. Mapping when a substance melts, boils, or sublimates under any pressure comes next: the **phase diagram**.

4 • Phase Diagrams

Read a pressure-temperature phase diagram: name the stable phase at any P, T , follow a constant-pressure or constant-temperature path and list the phase changes, and locate the triple point, critical point, and the normal melting and boiling points on the 1-atm line.

One map for all three states



Water can be ice, liquid, or steam. A phase diagram is the single map that says which one you get, for any pressure and temperature you choose.

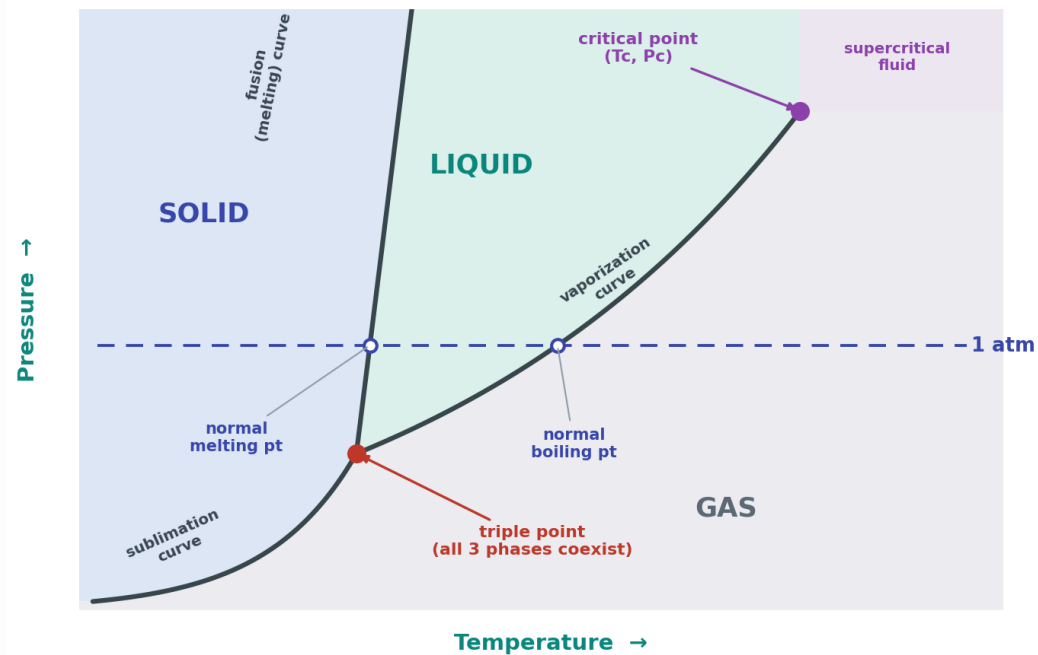
A phase diagram maps pressure vs temperature

A phase diagram plots **pressure (y)** against **temperature (x)** for one pure substance. Every point is one P,T pair. The region the point lands in names the stable phase: solid, liquid, or gas.

pick a pressure and a temperature → read off the stable phase

x-axis = Temperature · y-axis = Pressure · each point names one phase of one pure substance

Three regions, three dividing curves



Three **regions** are separated by three **curves**. On a curve two phases coexist, so **crossing a curve is a phase change**.

memory hook: each curve is named for the change across it
fusion: solid | liquid · vaporization: liquid | gas · sublimation: solid | gas

Two special points

triple point: the one P, T where solid, liquid, and gas all coexist
the single spot where all three curves meet

critical point (T_c, P_c): the top end of the vaporization curve
beyond it the liquid-gas boundary disappears → a supercritical fluid, neither true liquid nor gas

Above the critical temperature, no amount of pressure makes a separate liquid.

memory hook: triple means three phases meet · critical means the liquid-gas line ends

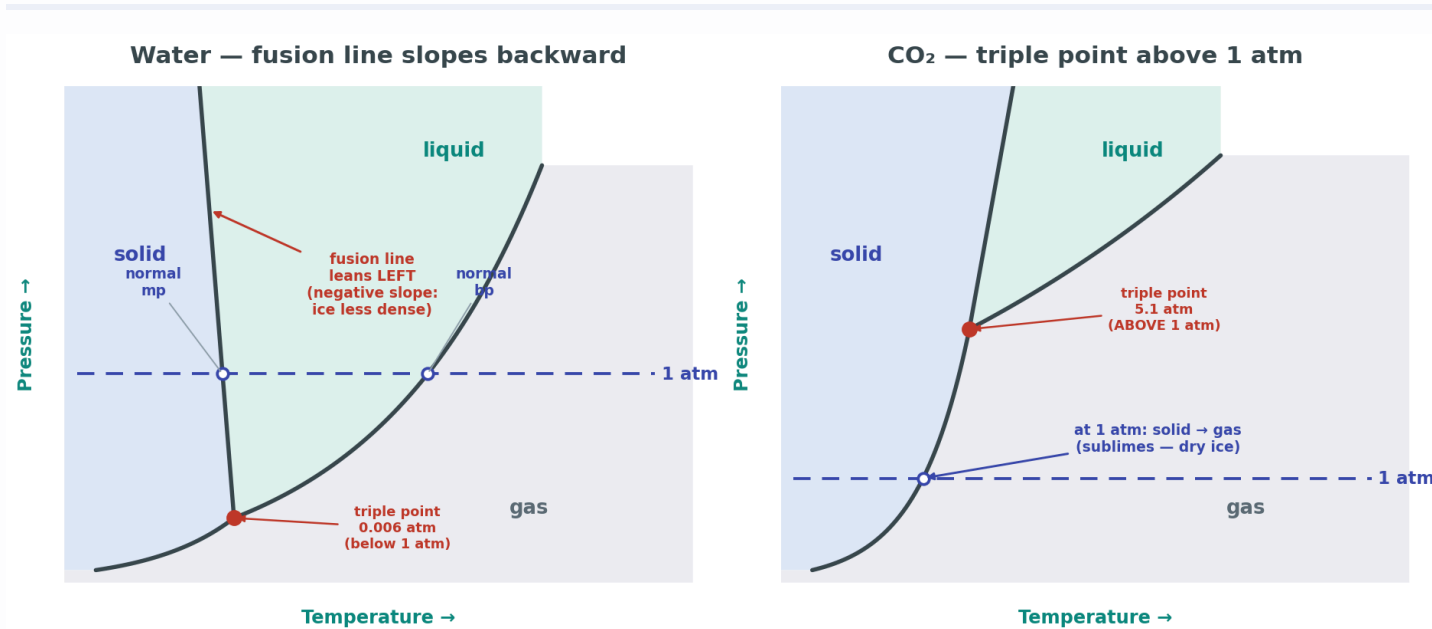
triple point sits low and left · critical point sits at the top of the vaporization curve

The 1-atm line gives the normal points

The 1-atm line crosses the fusion curve at the **normal melting point** and the vaporization curve at the **normal boiling point**. For water: 0 °C and 100 °C.

a horizontal path = constant pressure · a vertical path = constant temperature
follow the path and list every curve you cross: each crossing is one phase change

The solid-liquid slope: water breaks the rule



Squeezing favors the denser phase, usually the solid, so fusion curves slope up-and-right. **Water's** leans up-and-left: ice is less dense than the liquid, so pressure pushes ice toward water.

CO₂: triple point at 5.1 atm, above 1 atm
the 1-atm line never reaches the fusion curve · dry ice sublimates instead of melting



Reading a phase diagram

1. **Find the point.** T across, P up; its region names the phase.
2. **Choose the path.** Constant P: horizontal. Constant T: vertical.
3. **Cross the curves.** Each crossing is one phase change.
4. **Check the specials.** Triple point, critical point.



Worked example 1: heat a solid at constant pressure

start: solid, at a pressure just above the triple-point pressure

given: a pure substance with a normal (positive-slope) fusion curve · path: heat at constant pressure ·

wanted: the phases crossed

The sample starts cold, in the solid region. Heat it at constant pressure until it is well past its boiling point. List the phases it passes through.

✓ Worked example 1: solution

start: solid, just above the triple-point pressure
heat at constant pressure · normal fusion curve

Step 1 · Find the point

Step 2 · Choose the path

Step 3 · Cross the curves

solid → (cross fusion) → liquid → (cross vaporization) → gas
two curves crossed = two phase changes: melts, then boils

🧠 **Sense check:** Below the triple-point pressure, the same rightward path would cross only the **sublimation curve**: solid straight to gas, no liquid. ✓

✓ Worked example 1: the route on the map

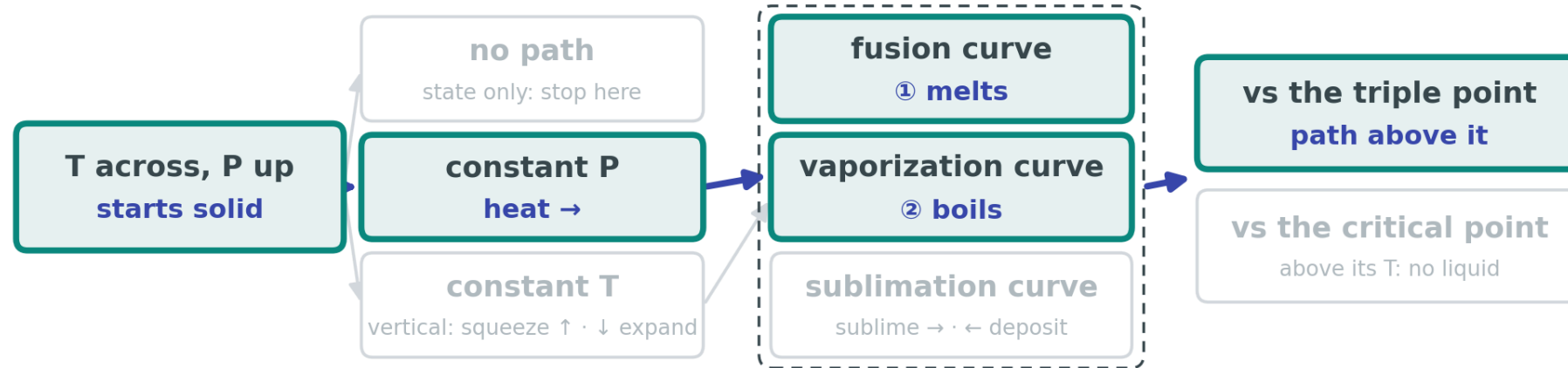
solid → (cross fusion) → liquid → (cross vaporization) → gas
 heat at constant pressure · the path runs above the triple-point pressure

1 · Find the point

2 · Choose the path

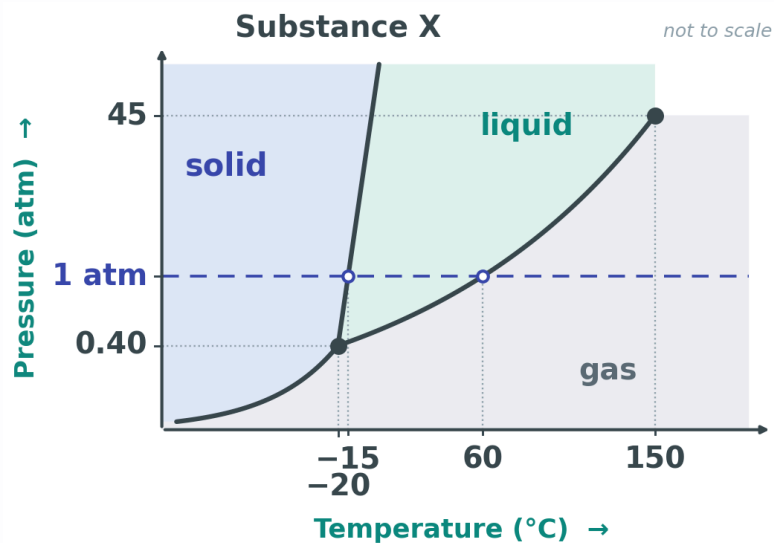
3 · Cross the curves

4 · Check the specials



🧠 **Sense check:** Above the triple point, both the fusion and the vaporization curves lie in the path. ✓

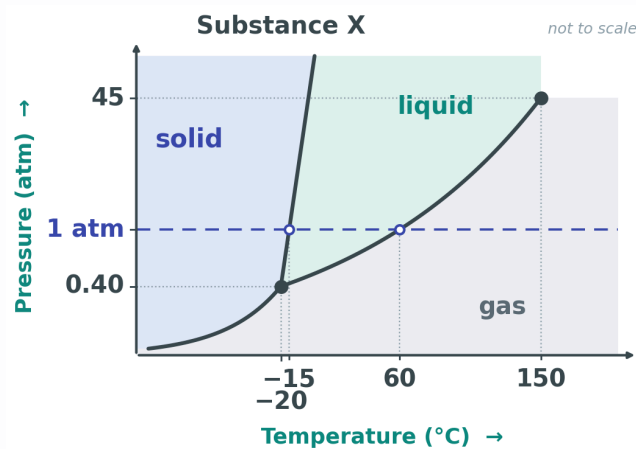
Worked example 2: reading substance X



substance X at 30 °C and 1 atm, heated at constant pressure to 100 °C
 wanted: the starting phase, and each phase change with its temperature

Read the diagram. Name the starting phase, then each phase change and its temperature.

✓ Worked example 2: solution



Step 1 · Find the point

Step 2 · Choose the path

Step 3 · Cross the curves

liquid (30 °C) → vaporization curve at 60 °C → gas (100 °C)
one curve crossed = one phase change · X boils at 60 °C, its normal boiling point

🧠 **Sense check:** The triple point (0.40 atm) lies below this path; the critical point (150 °C) lies past its end. ✓

✓ Worked example 2: the route on the map

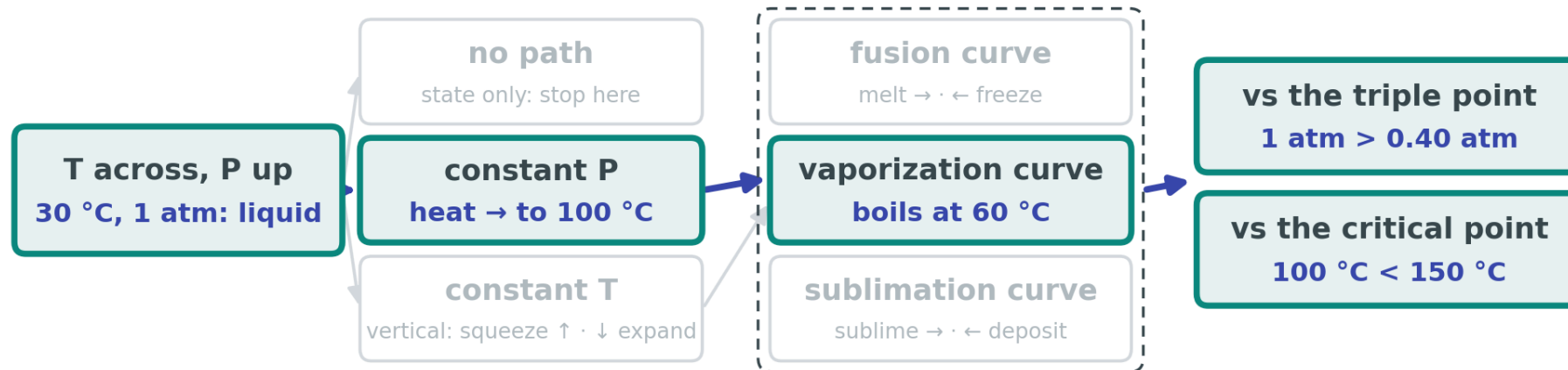
liquid (30 °C) → vaporization curve at 60 °C → gas (100 °C)
 substance X · 1 atm, above the 0.40-atm triple point · ends below the 150 °C critical temperature

1 · Find the point

2 · Choose the path

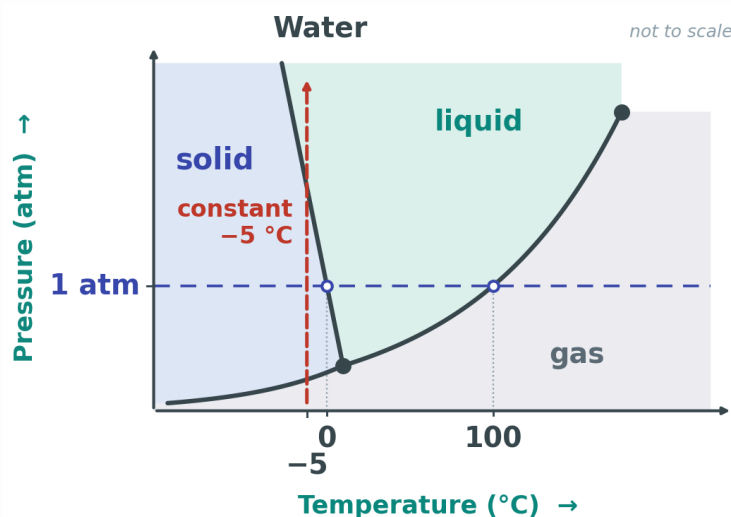
3 · Cross the curves

4 · Check the specials



🧠 **Sense check:** The path started past the fusion curve, so only one crossing remained. ✓

Your turn: squeeze water vapor at -5°C



starts as: ——— · first curve: ——— → becomes ——— · second curve: ——— → becomes ———

gas → (sublimation curve) → solid → (fusion curve) → liquid
two crossings · the left-leaning fusion curve means enough pressure melts ice below 0°C

⚠ Where this goes wrong

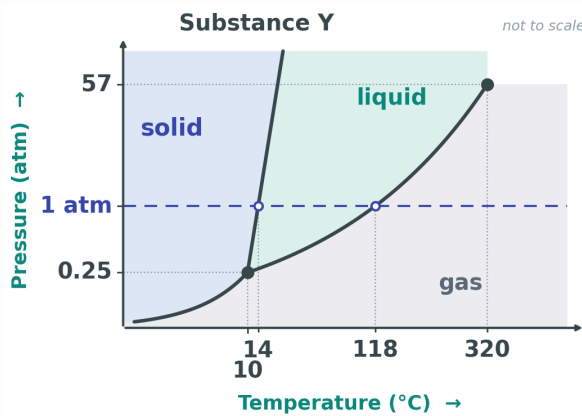
Swapping the axes. Temperature is the horizontal axis, pressure the vertical: read T across the bottom, P up the side, not the reverse.

Confusing the two special points. The triple point is where all three phases coexist; the critical point is where the liquid-gas distinction ends. They are different spots.

Assuming everything melts at 1 atm. If the triple point is above 1 atm (CO_2 , 5.1 atm), the 1-atm line never reaches the fusion curve: the solid sublimes instead of melting.

Treating water's fusion line as normal. Water's solid-liquid line slopes up-to-the-left; ice is less dense than water, so raising the pressure on ice can melt it.

Practice 1



Substance Y is warmed at 1 atm from 0 °C to 200 °C. What happens?

- A. Sublimes at 10 °C, straight from solid to gas
- B. Melts at 10 °C, then boils at 118 °C
- C. Melts at 14 °C, then boils at 118 °C
- D. Melts at 14 °C and is still liquid at 200 °C

✓ Practice 1 answer: C

1-atm line: fusion curve at $14\text{ }^{\circ}\text{C}$ · vaporization curve at $118\text{ }^{\circ}\text{C}$

→ **melts at $14\text{ }^{\circ}\text{C}$, boils at $118\text{ }^{\circ}\text{C}$** , answer C

A put the triple point on the path, but it sits at 0.25 atm, 0.75 atm below it. B read the triple-point temperature, $10\text{ }^{\circ}\text{C}$, as the melting point: $4\text{ }^{\circ}\text{C}$ too low. D took the critical point, $320\text{ }^{\circ}\text{C}$, as the boiling point: $202\text{ }^{\circ}\text{C}$ too high.

 **Sense check:** 1 atm is above Y's triple-point pressure, so Y melts and then boils, like any normal substance in open air. ✓



Practice 2

substance W: triple point 3.2 atm, $-28\text{ }^{\circ}\text{C}$ · critical point 48 atm, $96\text{ }^{\circ}\text{C}$
normal fusion curve · a gas at 20 atm and $120\text{ }^{\circ}\text{C}$ is cooled at constant pressure to $-60\text{ }^{\circ}\text{C}$

Which phase changes occur along the way?

- A. Deposition only (gas $\rightarrow$ solid)
- B. Condensation (gas $\rightarrow$ liquid), then freezing (liquid $\rightarrow$ solid)
- C. None: it starts above the critical temperature, so it never condenses
- D. Condensation only (gas $\rightarrow$ liquid)

✓ Practice 2 answer: B

20 atm: above the 3.2-atm triple point · below the 48-atm critical point

→ **condenses, then freezes**, answer B

The horizontal path runs 16.8 atm above the triple point, so cooling crosses the vaporization curve, then the fusion curve. It ends at $-60\text{ }^{\circ}\text{C}$, 32 $^{\circ}\text{C}$ below the triple-point temperature: solid.

A took the sublimation route, which runs only below 3.2 atm. D stopped at the liquid; the path continues past the fusion curve. C misread the critical point: the gas starts $24\text{ }^{\circ}\text{C}$ above the critical temperature, but cooling carries it below $96\text{ }^{\circ}\text{C}$, and at 20 atm, 28 atm under the critical pressure, it condenses.

 **Sense check:** Compare the path's pressure with both special points first. Between them, a cooling gas condenses and then freezes. ✓



Practice 3

a gas at $-40\text{ }^{\circ}\text{C}$ and 0.010 atm is compressed at constant temperature to 10 atm
substance P: triple point $-25\text{ }^{\circ}\text{C}$, 0.50 atm · critical point $160\text{ }^{\circ}\text{C}$, 42 atm · normal fusion curve

Name every phase change along this path.

- A. Deposition only (gas $\rightarrow$ solid)
- B. Deposition (gas $\rightarrow$ solid), then melting (solid $\rightarrow$ liquid)
- C. Condensation (gas $\rightarrow$ liquid), then freezing (liquid $\rightarrow$ solid)
- D. Condensation only (gas $\rightarrow$ liquid)

✓ Practice 3 answer: A

$-25\text{ }^{\circ}\text{C} - (-40\text{ }^{\circ}\text{C}) = 15\text{ }^{\circ}\text{C}$ below the triple point ·

the fusion curve leans right, away from $-40\text{ }^{\circ}\text{C}$ → **deposition only, answer A**

A vertical path is judged by its temperature. At $-40\text{ }^{\circ}\text{C}$ it runs left of the triple point, so it meets only the sublimation curve. The fusion curve rises from $-25\text{ }^{\circ}\text{C}$ toward higher temperatures and never reaches $-40\text{ }^{\circ}\text{C}$.

B gave P water's left-leaning fusion curve; P's leans right, so more pressure keeps it solid. C judged the path by pressure: 10 atm ends 9.5 atm above the triple point, but the temperature stays at $-40\text{ }^{\circ}\text{C}$. D assumed squeezing a gas always makes a liquid; below the triple-point temperature, no liquid region lies above the path.



Sense check: Below the triple-point temperature, squeezing a gas takes it straight to solid. ✓



Practice 4

water's vapor pressure at 60 °C: 0.196 atm

normal boiling point 100 °C · a sealed sample of water held at 60 °C and 0.196 atm

Which statement best describes the water?

- A. All gas: the pressure is below 1 atm
- B. All liquid: 60 °C is below the boiling point
- C. Half liquid and half gas, by mass
- D. Liquid and gas coexist, evaporating and condensing at equal rates

✓ Practice 4 answer: D

outside pressure = vapor pressure → on the vaporization curve · answer D
60 °C, 0.196 atm · on a curve two phases coexist · evaporation and condensation run at equal rates

On the liquid-gas border, molecules leave the liquid and return to it at the same rate. Both phases stay.

A read any pressure under 1 atm as gas; at 60 °C the gas region starts only below 0.196 atm. B used the normal boiling point at every pressure; 60 °C is 40 °C below it, but at 0.196 atm water boils at 60 °C itself. C read equilibrium as equal amounts; equal rates fix no ratio, so any mix of liquid and vapor sits on the curve.

 **Sense check:** Above 0.196 atm: liquid. Below it: gas. Exactly at it: both, the same balance as the vapor over a liquid in a sealed flask. ✓



Practice 5

a solid at 55 atm and $-70\text{ }^{\circ}\text{C}$ is heated at constant pressure to $180\text{ }^{\circ}\text{C}$
substance R: triple point $-30\text{ }^{\circ}\text{C}$, 0.60 atm · critical point $135\text{ }^{\circ}\text{C}$, 44 atm · normal fusion curve

What does the sample go through as it warms?

- A. Melting (solid $\rightarrow$ liquid), then boiling (liquid $\rightarrow$ gas)
- B. Sublimation only (solid $\rightarrow$ gas)
- C. Melting, then a smooth change to a supercritical fluid, with no boiling
- D. Melting, then boiling, then a change to a supercritical fluid
- E. Melting only: it is still a liquid at $180\text{ }^{\circ}\text{C}$

✓ Practice 5 answer: C

$55 \text{ atm} - 44 \text{ atm} = 11 \text{ atm}$ above the critical point · $180 \text{ }^{\circ}\text{C} - 135 \text{ }^{\circ}\text{C} = 45 \text{ }^{\circ}\text{C}$ past it

→ **melts, then turns supercritical, answer C**

Above the triple point, the path crosses the fusion curve: the solid melts. The vaporization curve ends at 44 atm, below the path, so nothing boils. Past 135 °C the liquid turns supercritical.

A missed that the path runs 11 atm above the critical pressure, where the vaporization curve has ended. D checked the end temperature but still drew a boiling crossing above 44 atm. B judged a horizontal path by its temperature: $-70 \text{ }^{\circ}\text{C}$ is $40 \text{ }^{\circ}\text{C}$ below the triple point, but 55 atm sits 54.4 atm above it. E stopped at the liquid; above both 135 °C and 44 atm, liquid and gas are no longer distinct.

 **Sense check:** Above the critical pressure, heating never boils: the liquid turns into a supercritical fluid. ✓



Check yourself

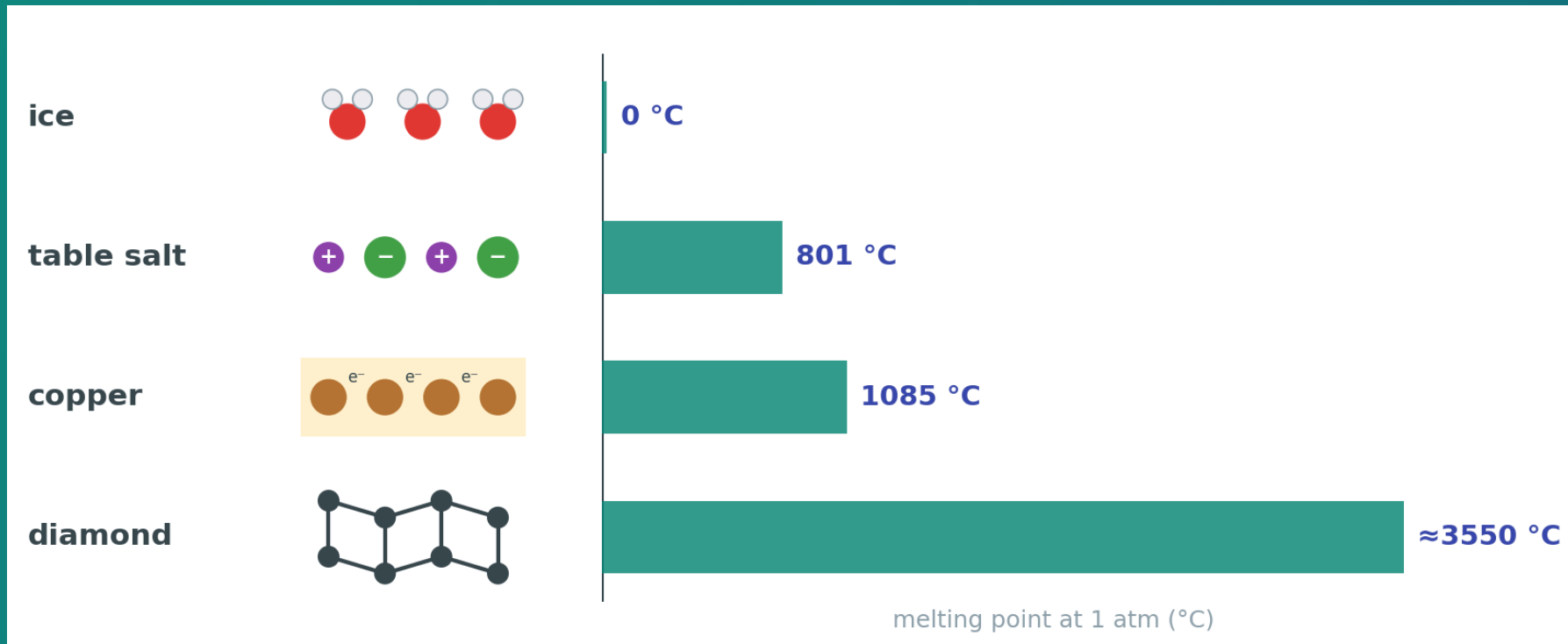
1. A substance with a normal fusion curve is heated at a constant pressure above its triple point. Which curve does the path cross first, and what phase change is it?
2. Why can raising the pressure on ice just below 0 °C melt it, when raising the pressure on most solids does the opposite?

The solid region of any phase diagram hides very different kinds of solid. Sorting them by the particles they are built from explains why some melt near room temperature and others far above 1000 °C.

5 • Types of Solids

Classify a solid as crystalline or amorphous and, for a crystal, sort it into one of the four types (ionic, metallic, covalent-network, molecular) from the particle at its lattice points and the force holding them, then predict its melting point, hardness, and conductivity, and count the atoms in a simple, body-centered, or face-centered cubic unit cell.

Four solids, four melting points



Ice melts at 0 °C. Diamond stays solid until about 3550 °C. The particles inside each solid, and what holds them together, set the difference.

Crystalline vs amorphous

A **crystalline** solid has a regular, repeating lattice, so it melts sharply at one temperature. An **amorphous** solid has no long-range order; heated, it softens gradually over a range.

crystalline = ordered, repeating lattice → sharp melting point

amorphous = no long-range order → softens over a range · glass, rubber, most plastics

Two questions sort every crystal

Two answers classify a crystalline solid: the particle at each lattice point, and the force holding those particles. The force sets the properties: stronger force, higher melting point, harder solid.

particle + force → type → properties
ionic · metallic · covalent network · molecular

memory hook: metal only, metallic · metal with nonmetal, ionic · nonmetals only, molecular

except the short network list: C (diamond, graphite), Si, SiO₂, SiC · a polyatomic ion also means ionic (NH₄Cl)

Ionic & metallic solids

Ionic: positive & negative ions · electrostatic ionic bonds
high mp, hard but brittle; conducts only when molten or dissolved · NaCl, MgO

Metallic: metal cations in a sea of shared electrons · metallic bonding
melting point varies, malleable & ductile; conducts as a solid · Cu, Fe, Au

The mobile sea of electrons lets a metal bend without shattering and carry a current.

memory hook: metal electrons are already free · ions must be set free
a metal conducts as a solid · an ionic solid conducts only once melted or dissolved

Covalent-network & molecular solids

Covalent network: atoms joined in one continuous covalent network
very high mp, very hard, usually nonconducting · diamond, SiO₂ (quartz), SiC

Molecular: whole molecules held by intermolecular forces
low mp, soft, nonconducting · ice, dry ice (CO₂), sugar · solid argon sorts here too: lone atoms held by dispersion

Graphite is the exception among network solids: its sheets slide (soft, a lubricant), and its delocalized electrons conduct.

The whole picture

The four types of crystalline solid

Type	Particles at the lattice points	Force holding them together	Typical properties (melting point · hardness · conductivity)	Example
Ionic	positive & negative ions	electrostatic ionic bonds	high melting point; hard but brittle; conducts only molten/dissolved	NaCl (table salt)
Metallic	metal cations in a sea of shared e ⁻	metallic bonding (delocalized e ⁻)	melting point varies; malleable & ductile; conducts as a solid	Cu, Fe, Au
Covalent network	atoms linked in one continuous network	covalent bonds throughout crystal	very high melting point; very hard; nonconducting (graphite conducts)	diamond, SiO₂ (quartz)
Molecular	discrete molecules	intermolecular forces (dispersion, dipole, H-bond)	low melting point; soft; nonconducting	ice, CO₂, sugar

Melting point tracks the holding force: covalent network ≥ ionic > metallic > molecular

Read any row across: the particle sets the force, and the force sets every property.



Classify a solid in three steps

1. **Name the particle:** ions, metal atoms, network atoms, or molecules.
2. **Name the force:** ionic, metallic, covalent network, or intermolecular.
3. **Predict the properties** from that force: melting point, hardness, conductivity.



Worked example 1: calcium chloride

CaCl_2 : a road de-icer

Ca is a metal · Cl is a nonmetal · wanted: the solid type, then its melting point, hardness, and conductivity

Classify solid calcium chloride, then predict its properties.

✓ Worked example 1: solution

CaCl_2 : a road de-icer

Ca is a metal · Cl is a nonmetal

Step 1 · Name the particle

Step 2 · Name the force

Ca^{2+} and Cl^- ions → ionic bonds → **ionic solid**

Step 3 · Predict the properties

ionic solid →

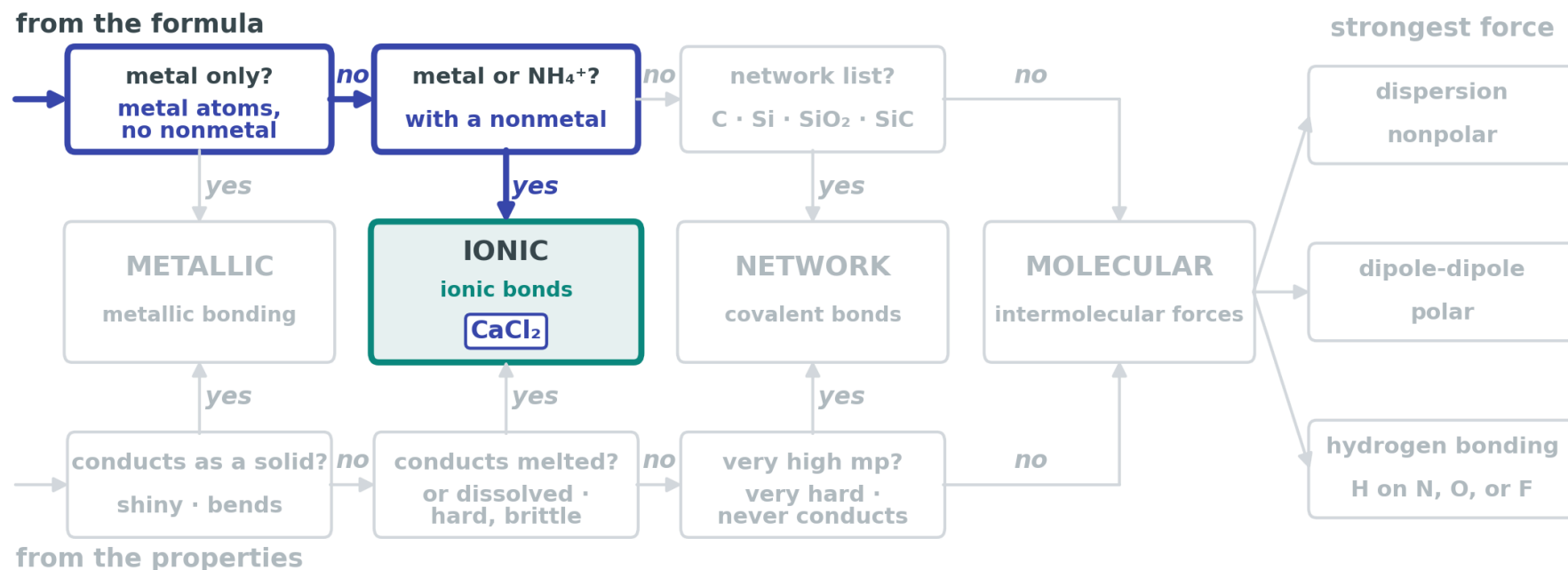
high melting point · hard but brittle · conducts only when molten or dissolved

 **Sense check:** CaCl_2 melts at $772\text{ }^\circ\text{C}$, near table salt's $801\text{ }^\circ\text{C}$. Dissolved on a road, its free ions conduct. ✓

✓ Worked example 1: the route on the map

CaCl₂: an ionic solid

metal only? no, Cl is a nonmetal · a metal or NH₄⁺ with a nonmetal? yes, Ca with Cl



 **Sense check:** The second question answered yes. The network list never came up. ✓

Worked example 2: an unknown shiny solid

unknown solid: shiny, melts at 1085 °C

bends without breaking · conducts electricity as a solid · wanted: its type and the particle feature behind it

Only the properties are known. Work the three steps from this evidence.

✓ Worked example 2: solution

unknown solid: shiny, melts at 1085 °C
bends without breaking · conducts as a solid

Step 1 · Name the particle

Step 2 · Name the force

cations + mobile electrons → metallic bonding → **metallic solid**

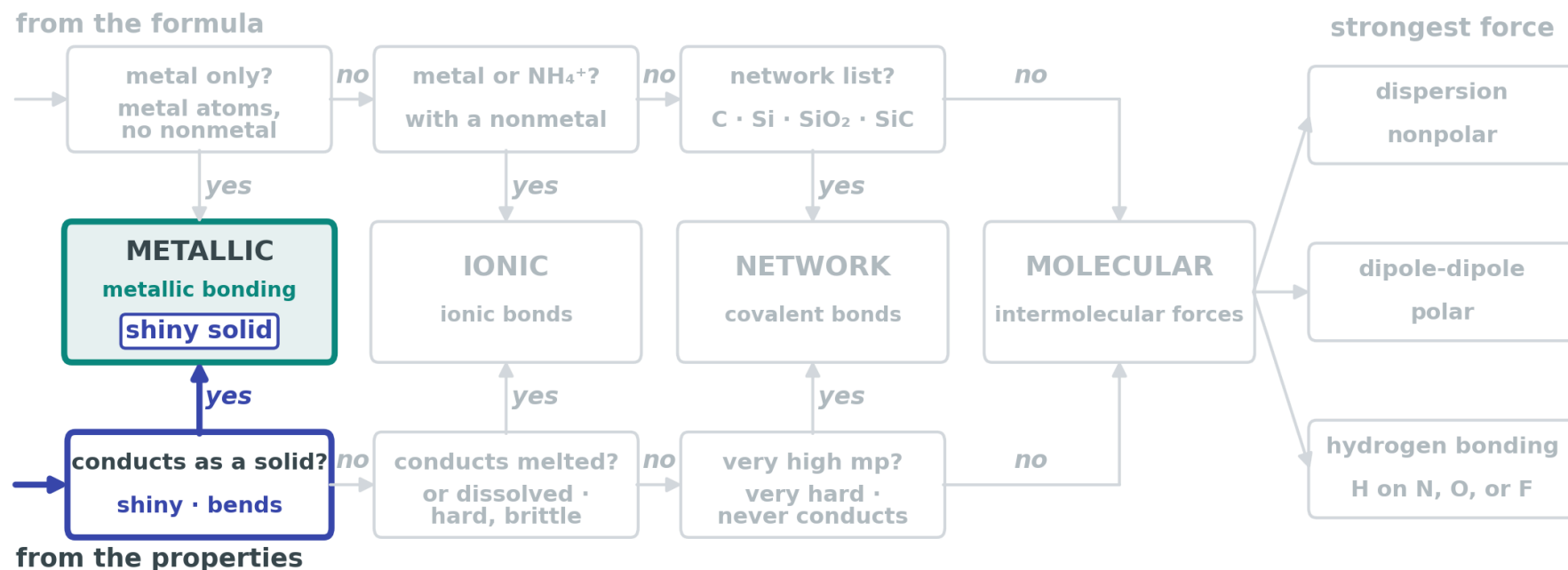
Step 3 · Predict the properties

metallic: shiny · malleable · conducts as a solid · mp varies
every observed property matches · this is copper

 **Sense check:** NaCl answers the conductivity test the other way. Its ions stay locked in the lattice, so it conducts only once melted or dissolved. ✓

✓ Worked example 2: the route on the map

unknown shiny solid: a metallic solid
no formula given · conducts as a solid? yes



🧠 **Sense check:** Only properties were known, so the bottom row sorted it. One yes settled it. ✓

Your turn: iodine

I_2 : a nonmetal element built of I_2 molecules
 nonpolar molecule · wanted: the particle, the force, the properties

step	solid iodine
1 · name the particle	_____
2 · name the force	_____
3 · predict the properties	_____ melting point, soft, _____

Fill the blanks. Iodine and diamond are both nonmetal elements; check the network list.

$I_2 \rightarrow$ molecular solid
 particle: I_2 molecules · force: dispersion (intermolecular) · low mp (114 °C), soft, nonconducting

⚠ Where this goes wrong

Ionic solids conduct as solids. They do not. The ions are locked in place. An ionic solid conducts only once molten or dissolved, when the ions can move.

Dry ice is a network solid like SiO_2 . No. CO_2 freezes as a molecular solid: discrete molecules, weak forces, sublimates at $-78\text{ }^\circ\text{C}$. SiO_2 is a covalent network that melts near $1700\text{ }^\circ\text{C}$.

A wide melting range means crystalline. Backwards. A sharp melting point marks a crystal. Softening over a range marks an amorphous solid.



Practice 1

an unknown colorless solid

extremely hard · melts near 2000 °C · does not conduct as a solid or when molten

Which type of solid is it?

- A. Ionic: hard, with a very high melting point, like most salts
- B. Metallic: only a metal stays solid past 1000 °C
- C. Covalent network: hard, very high melting point, no ions to carry current
- D. Molecular: it does not conduct, so it must be built of molecules

✓ Practice 1 answer: C

extremely hard · very high mp · no conduction, solid or molten

→ **covalent network**, answer C

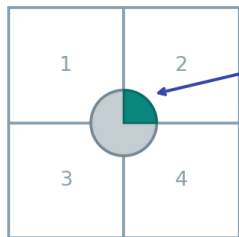
A matched hardness and melting point but skipped the molten test: a melted ionic solid conducts. B ignored the conductivity; a metal conducts as a solid. D read only the conductivity; a molecular solid melts low and is soft, never near 2000 °C.

 **Sense check:** Quartz and silicon carbide fit this profile. The whole crystal is one covalent network, so melting means breaking covalent bonds. ✓

Counting atoms in a cubic unit cell

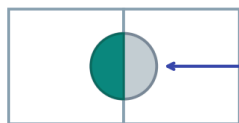
A **unit cell** is the smallest repeating box of a crystal. Shared atoms count in part: a **corner** atom $\frac{1}{8}$, a **face** atom $\frac{1}{2}$, a **body-center** atom a full 1.

corner atom



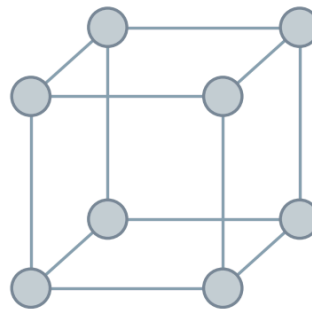
x2 layers → 8 cells share it
→ $\frac{1}{8}$ each

face atom



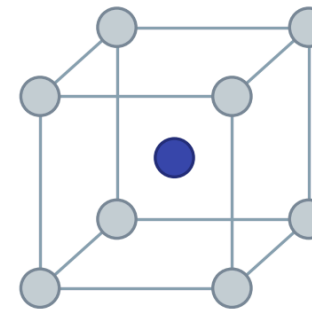
2 cells → $\frac{1}{2}$

Simple cubic (sc)



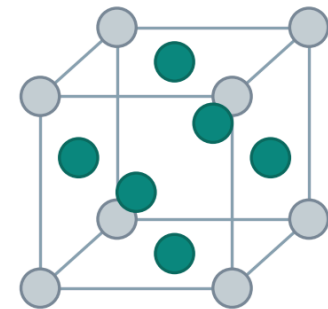
8 corners

Body-centered cubic (bcc)



8 corners + 1 body center

Face-centered cubic (fcc)



8 corners + 6 face centers

grey = corner blue = body center teal = face center



Count the atoms in a unit cell

1. **Sort the positions.** Count the corner, face, and body-center atoms.
2. **Apply each share.** Corner $\frac{1}{8}$, face $\frac{1}{2}$, body center 1.
3. **Add the shares.** The sum is the atoms per cell.



Worked example 3: iron

iron: body-centered cubic

atoms drawn at 8 corners + 1 body center · wanted: atoms per unit cell

A common first count: 9 atoms, one for every sphere in the drawing.

Count the atoms that belong to one unit cell.

✓ Worked example 3: solution

iron: body-centered cubic
8 corners + 1 body center drawn

Step 1 · Sort the positions

Step 2 · Apply each share

$$8 \text{ corners} \times \frac{1}{8} = 1 \quad \cdot \quad 1 \text{ body center} \times 1 = 1$$

Step 3 · Add the shares

$$1 + 1 = 2 \text{ atoms per unit cell}$$

 **Sense check:** The first count of 9 treated every drawn sphere as whole. Eight of them are mostly in neighboring cells. ✓

Take-home: count shares, not spheres

corner $\frac{1}{8}$ · face $\frac{1}{2}$ · body center 1

a drawing shows every sphere whole · only its share belongs to one cell

memory hook: corners split 8 ways, faces split 2 ways, the center keeps its own

8 cells meet at a corner · 2 cells share a face · the body center sits inside one cell

A unit-cell count is always a sum of shares.



Practice 2

**an unknown gray solid: soft enough to scratch with a fingernail, melts at 327 °C
conducts electricity as a solid · atoms at the 8 corners and 6 face centers of a cubic unit cell**

What type of solid is it, and how many atoms belong to one unit cell?

- A. Metallic solid · 4 atoms per cell
- B. Molecular solid · 4 atoms per cell
- C. Metallic solid · 7 atoms per cell
- D. Metallic solid · 14 atoms per cell

✓ Practice 2 answer: A

conducts as a solid → metallic · $8 \text{ corners} \times \frac{1}{8} + 6 \text{ faces} \times \frac{1}{2} = 1 + 3$

→ **metallic, 4 atoms per cell**, answer A

Conductivity is the sharpest test: only a metal conducts as a solid. Soft and 327°C still fit, because metallic melting points vary widely. Then count shares, not spheres.

B let the softness and the modest melting point outvote the conductivity; a molecular solid never conducts. C counted each face atom whole: $1 + 6 = 7$. D counted every drawn sphere whole: $8 + 6 = 14$.

 **Sense check:** This is lead: soft, low melting, and conducting like any metal. A face-centered cubic cell holds 4 atoms. ✓



Extra practice 1

$\text{KBr} \cdot \text{NH}_3 \cdot \text{O}_2 \cdot \text{SiO}_2$, each as a solid

potassium bromide · ammonia · oxygen · silicon dioxide (quartz)

Which order runs from the lowest to the highest melting point?

- A. $\text{NH}_3 < \text{O}_2 < \text{SiO}_2 < \text{KBr}$
- B. $\text{O}_2 < \text{NH}_3 < \text{KBr} < \text{SiO}_2$
- C. $\text{NH}_3 < \text{O}_2 < \text{KBr} < \text{SiO}_2$
- D. $\text{O}_2 < \text{NH}_3 < \text{SiO}_2 < \text{KBr}$
- E. $\text{O}_2 < \text{SiO}_2 < \text{NH}_3 < \text{KBr}$

✓ Extra practice 1 answer: B

$\text{KBr} \cdot \text{NH}_3 \cdot \text{O}_2 \cdot \text{SiO}_2$, each as a solid

O_2 : molecular, dispersion only · NH_3 : molecular, H on N · KBr : ionic · SiO_2 : covalent network

O_2 : dispersion < NH_3 : hydrogen bonding < KBr : ionic bonds < SiO_2 : covalent network

→ **$\text{O}_2 < \text{NH}_3 < \text{KBr} < \text{SiO}_2$** , answer B

A ranked by molar mass: $17.03 < 32.00 < 60.09 < 119.00$ g/mol. The force sets the melting point, not the mass. C ranked the two molecular solids by size and missed the H on N in NH_3 . D put ionic above network; melting KBr separates ions, but melting quartz breaks covalent bonds through the whole crystal. E read SiO_2 as a molecule like CO_2 .

 **Sense check:** O_2 melts at -219°C , NH_3 at -78°C , KBr at 734°C , and quartz near 1700°C . ✓

Extra practice 2

same type: the same particle at the lattice points, held by the same force
ionic · metallic · covalent network · molecular

Which pair forms the same type of crystalline solid?

- A. NH_4I and CaO
- B. CO_2 and SiO_2
- C. C (graphite) and Cu
- D. Si and Al
- E. NH_4Br and HBr

✓ Extra practice 2 answer: A

NH_4I and CaO : both ionic

NH_4^+ with I^- · Ca^{2+} with O^{2-} · a metal or NH_4^+ with a nonmetal both times

NH_4^+ and I^- ions · Ca^{2+} and O^{2-} ions → **both ionic solids**, answer A

B matched the formulas. CO_2 forms molecules (dry ice); SiO_2 is on the network list. C matched the conductivity. Graphite conducts, but it is a covalent network; Cu is metallic. D matched the shine. Al is metallic; Si is on the network list. E applied the nonmetals-only rule to NH_4Br . NH_4^+ makes it ionic; HBr is molecular.

 **Sense check:** A polyatomic ion counts as an ion. NH_4^+ with any anion makes an ionic solid, just as a metal does. ✓

Extra practice 3

perovskite: a calcium titanium oxide, cubic unit cell
Ca at the 8 corners · one Ti at the body center · O at the 6 face centers

What is the formula of perovskite?

- A. CaTiO_6
- B. CaTiO_3
- C. Ca_8TiO_6
- D. Ca_2TiO_3
- E. TiO_3

✓ Extra practice 3 answer: B

perovskite: a calcium titanium oxide, cubic unit cell

Ca^{2+} at 8 corners · Ti^{4+} at 1 body center · O^{2-} at 6 face centers

Ca: $8 \times \frac{1}{8} = 1$ · Ti: $1 \times 1 = 1$ · O: $6 \times \frac{1}{2} = 3 \rightarrow \text{CaTiO}_3$, answer B

A counted each face ion whole: 6 O. C counted every drawn sphere whole: 8 Ca and 6 O. D gave each corner $\frac{1}{4}$, the flat-square share: $8 \times \frac{1}{4} = 2$ Ca. E left out the corners, as if they belonged only to neighboring cells.

🧠 **Sense check:** Charges: $+2 + 4 + 3(-2) = 0$. The others leave a net charge: A -6 , C $+8$, D $+2$, E -2 . ✓



Check yourself

1. Diamond and dry ice are both built only from nonmetal atoms, yet diamond melts near $3550\text{ }^{\circ}\text{C}$ while dry ice sublimates at $-78\text{ }^{\circ}\text{C}$. Which is covalent network and which is molecular, and what force explains the gap?
2. Sugar and table salt both dissolve in water, but only one solution conducts. Which one, and what does that say about each solid's particles?

Dissolved ions carry current; dissolved molecules do not. That difference runs through the solutions unit.

Can you...?

- ☐ identify the intermolecular forces present in a substance and rank their relative strength?
- ☐ explain surface tension, viscosity, capillary action, and vapor pressure from the strength of intermolecular forces?
- ☐ relate intermolecular-force strength to boiling point and rank substances by boiling point?
- ☐ read a phase diagram: the stable phase at a given pressure and temperature, the triple and critical points, and the phase changes along a path?
- ☐ classify a solid as ionic, metallic, covalent network, or molecular, predict its properties, and count the atoms in a cubic unit cell?

If any box stays empty, the practice site has a drill for it. 