

Solids & Liquids

Preparation for General Chemistry · Dr. Karmach

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

- Name the six changes of state, label each endothermic or exothermic, and read a heating or cooling curve
- Calculate the heat for warming steps with $q = mc\Delta T$ and for phase changes with the heats of fusion and vaporization, and add them along a heating curve
- Identify the intermolecular forces in a substance and rank substances by boiling point and vapor pressure
- Explain vapor pressure, boiling point, surface tension, and viscosity from intermolecular forces, including why boiling point changes with outside pressure
- Read a phase diagram: the stable phase at a given pressure and temperature, the triple point, and the normal melting and boiling points
- Classify a solid as ionic, metallic, molecular, or network and predict its melting point, hardness, and conductivity

Today's route

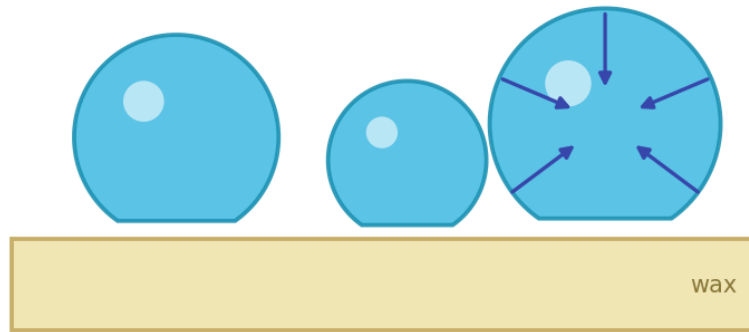
1. Intermolecular Forces
2. Properties of Liquids
3. IMFs & Boiling Point
4. Phase Diagrams
5. Heat of a Phase Change
6. Heating & Cooling Curves
7. Types of Solids

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

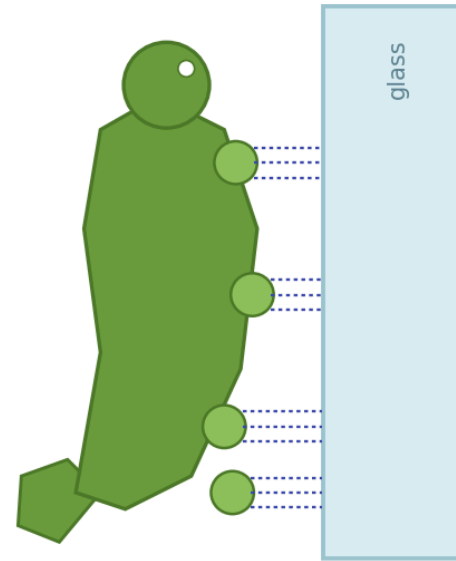
water on a waxed car



the water pulls itself into round beads

instead of spreading flat

a gecko on a glass wall



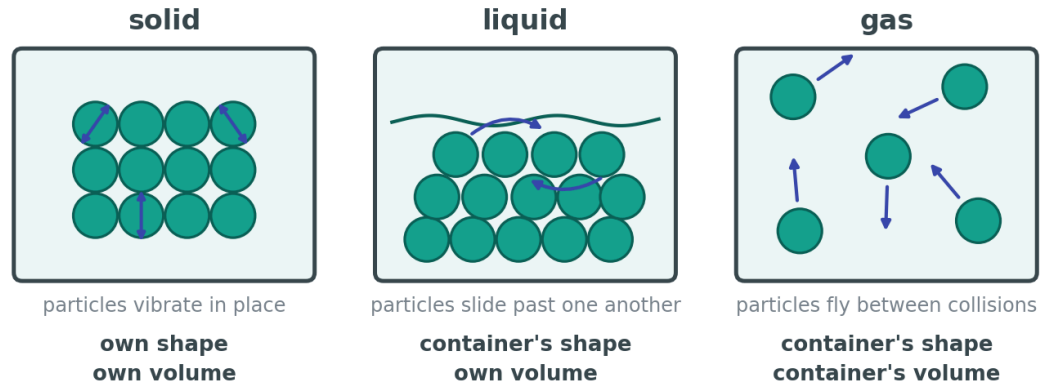
countless faint pulls hold its weight

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.

What decides solid, liquid, or gas

same particles, three arrangements

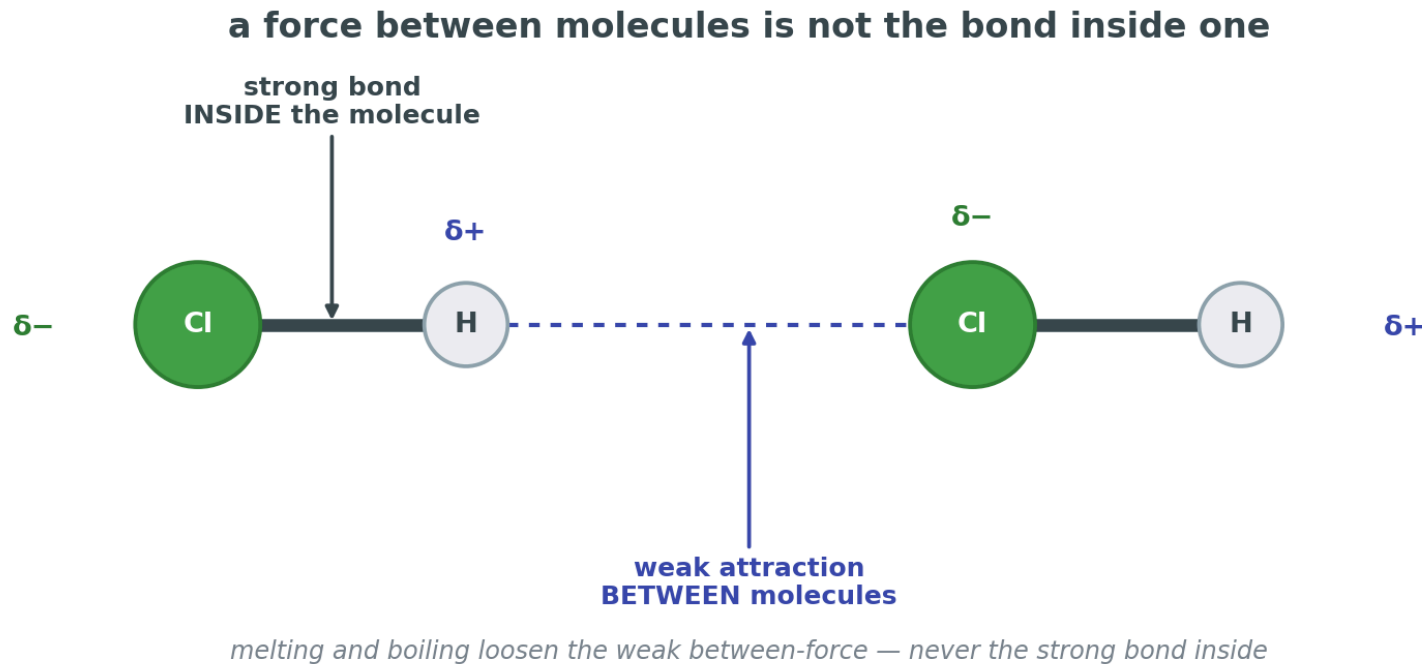


spacing and motion name the state

Particles are always moving, and they attract one another. When motion wins, the particles fly apart as a gas. When attraction wins, they stay in contact as a liquid or a solid.

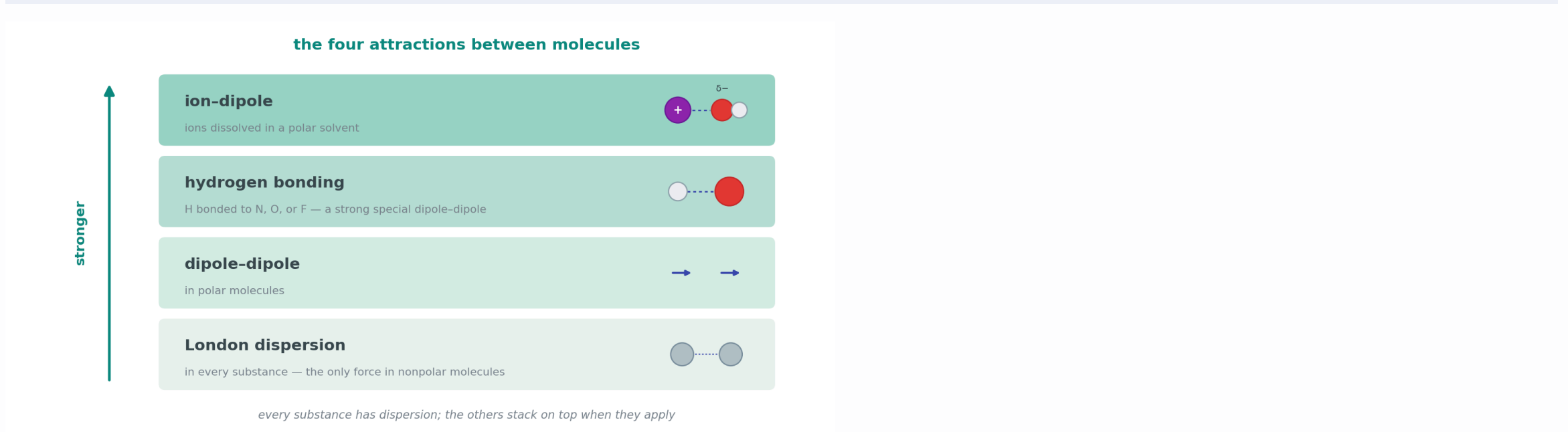
at room temperature: CH_4 (16.04 g/mol) is a gas · H_2O (18.02 g/mol) is a liquid
nearly the same mass · water molecules attract one another far more strongly

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.

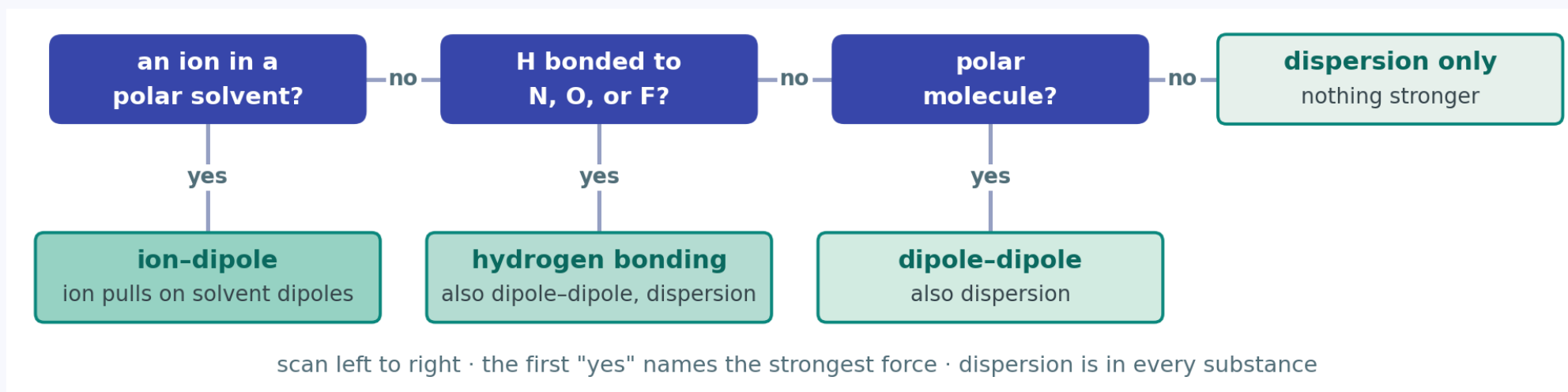
$\text{F}_2 \cdot \text{Cl}_2 \cdot \text{Br}_2 \cdot \text{I}_2$: all nonpolar

molar mass 38.00 → 70.90 → 159.80 → 253.80 g/mol · 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.**





Guided example: chloroform

CHCl_3 : carbon bonded to one H and three Cl
tetrahedral · wanted: every force present, and the strongest

Chloroform was one of the first surgical anesthetics. Name every intermolecular force in liquid chloroform, then the strongest.

Scan in order: an ion first, then an H on N, O, or F, then polarity.

✓ Guided example: identify the pieces

CHCl_3 : carbon bonded to one H and three Cl
tetrahedral · wanted: every force present, and the strongest

Step 1 · Identify the pieces

an ion in a polar solvent? no
move 1 · CHCl_3 is a neutral molecule, not a dissolved ion

H bonded to N, O, or F? no
move 2 · the only H sits on carbon · Cl is not N, O, or F

polar molecule? yes
move 3 · one H and three Cl around carbon · the bond dipoles do not cancel

🧠 **Sense check:** Three questions, answered no, no, yes. The first yes is polarity.

✓ Guided example: name the forces

CHCl_3 : a neutral, polar molecule
no ion · no H on N, O, or F · polar

Step 2 · Name every force present

polar · H on C only → London dispersion + dipole-dipole

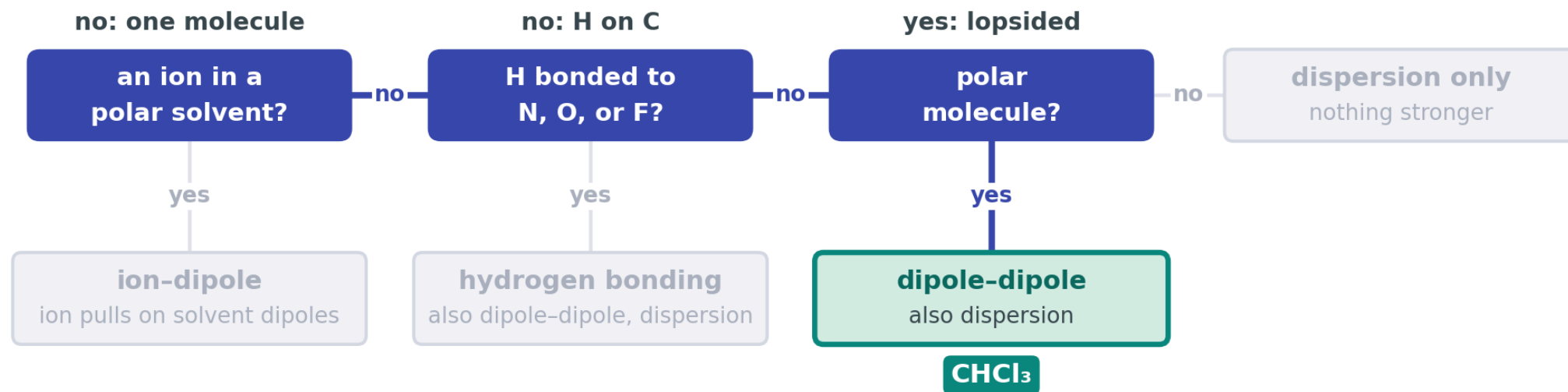
Step 3 · Pick the strongest

CHCl_3 → strongest force: dipole-dipole
dipole-dipole outranks dispersion · no hydrogen bonding, no ion-dipole

 **Sense check:** Chloroform holds three Cl atoms, but Cl is not a hydrogen-bond atom and the H sits on carbon. Dipole-dipole is the strongest. ✓

✓ Guided example: the route on the chart

CHCl₃: carbon bonded to one H and three Cl
 found: dispersion + dipole-dipole · strongest: dipole-dipole



 **Sense check:** No, no, yes: chloroform exits at dipole-dipole. Dispersion comes along, as it does in every substance. ✓



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**

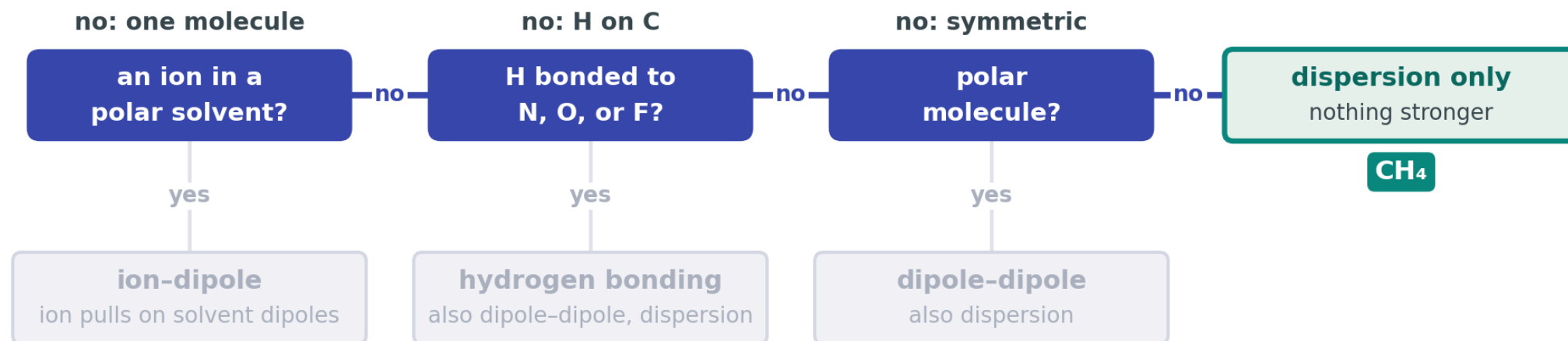
Step 3 · Pick the strongest

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

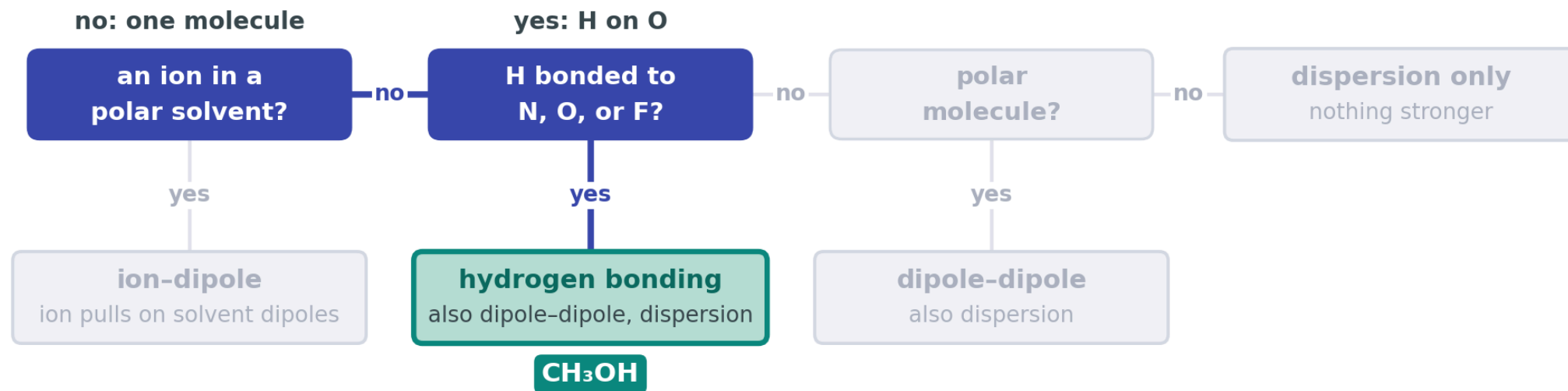
$\text{CH}_3\text{OH} \rightarrow$ strongest force: hydrogen bonding
H-O present · a strong special dipole-dipole, above ordinary dipole-dipole and dispersion

🧠 **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

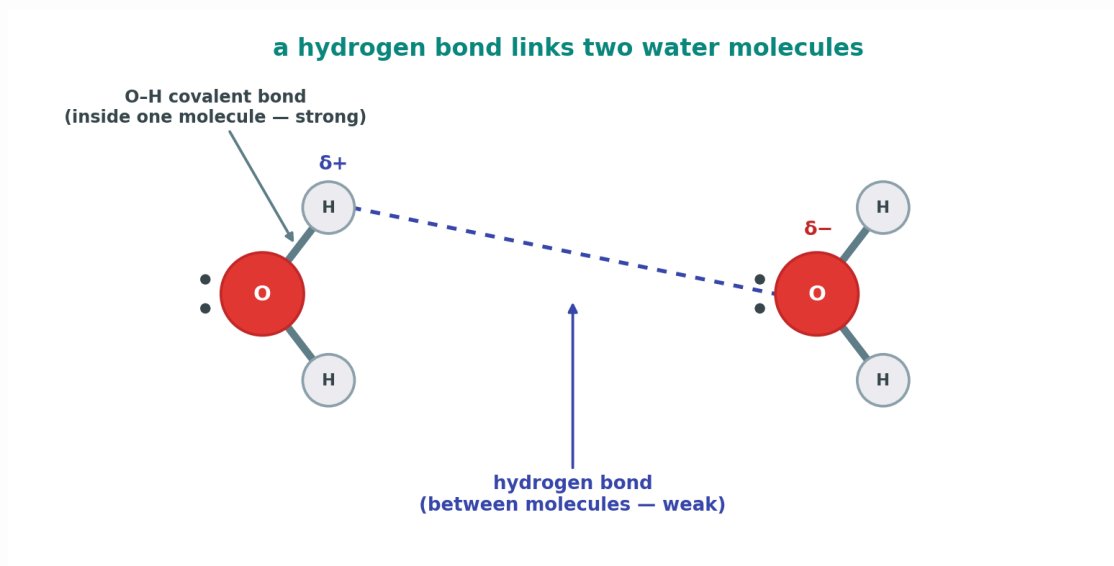
CH₃OH: an O-H group on a carbon

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.



Practice 1



fluoromethane · hydrogen bromide · hydrogen peroxide · silane

Which substance forms hydrogen bonds in the pure liquid?

- A. CH_3F
- B. H_2O_2
- C. HBr
- D. SiH_4

✓ Practice 1 answer: B

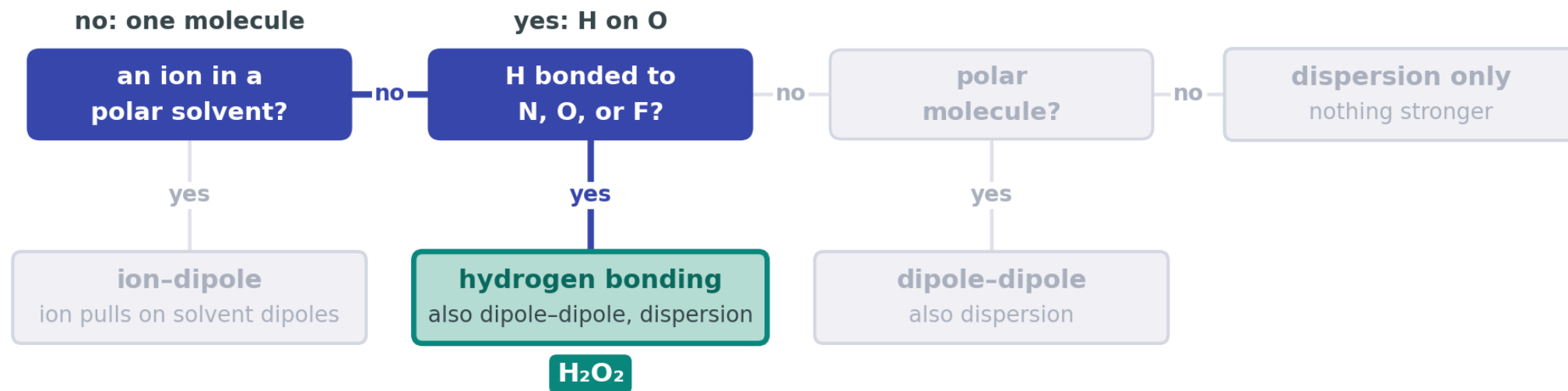
H_2O_2 : H-O-O-H → hydrogen bonding · answer B
each H bonded directly to O · CH_3F : H on C · HBr: H on Br · SiH_4 : H on Si

A has fluorine, but every H sits on carbon; the F carries no H. C puts H on bromine, which is not N, O, or F. D has four H atoms, all on silicon.

🧠 **Sense check:** The H must sit on N, O, or F itself. One of those atoms somewhere in the formula is not enough. ✓

✓ Practice 1: the route on the chart

$\text{H}_2\text{O}_2 \rightarrow$ strongest force: hydrogen bonding · answer B
a molecule, no ion · each H bonded directly to O



 **Sense check:** An H on O exits at the second question. The other three never reach that exit: their H atoms sit on C, Br, and Si. ✓

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 2

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 2 answer: C

HF → strongest force: hydrogen bonding · answer C

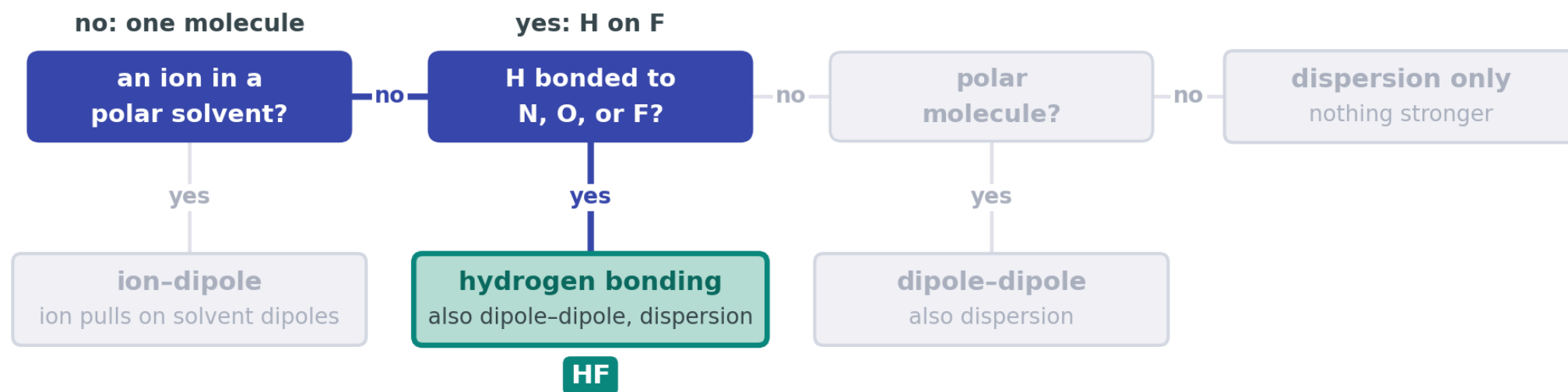
H bonded directly to F · a strong special dipole-dipole, the strongest force here

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.

✓ Practice 2: the route on the chart

HF → strongest force: hydrogen bonding · answer C
a molecule, no ion · H bonded directly to F



🧠 **Sense check:** An H on F exits at the second question. HF is polar too, but the scan never needs to ask. ✓

 Practice 3

PF₃: phosphorus bonded to three F
phosphorus trifluoride

Which list names every intermolecular force present in liquid PF₃?

- A. dispersion and dipole-dipole
- B. dispersion only
- C. dipole-dipole only
- D. dispersion, dipole-dipole, and hydrogen bonding

✓ Practice 3 answer: A

$\text{PF}_3 \rightarrow$ dispersion + dipole-dipole · answer A

a molecule, no ion · no H at all · one lone pair on P $\rightarrow$ trigonal pyramidal $\rightarrow$ polar

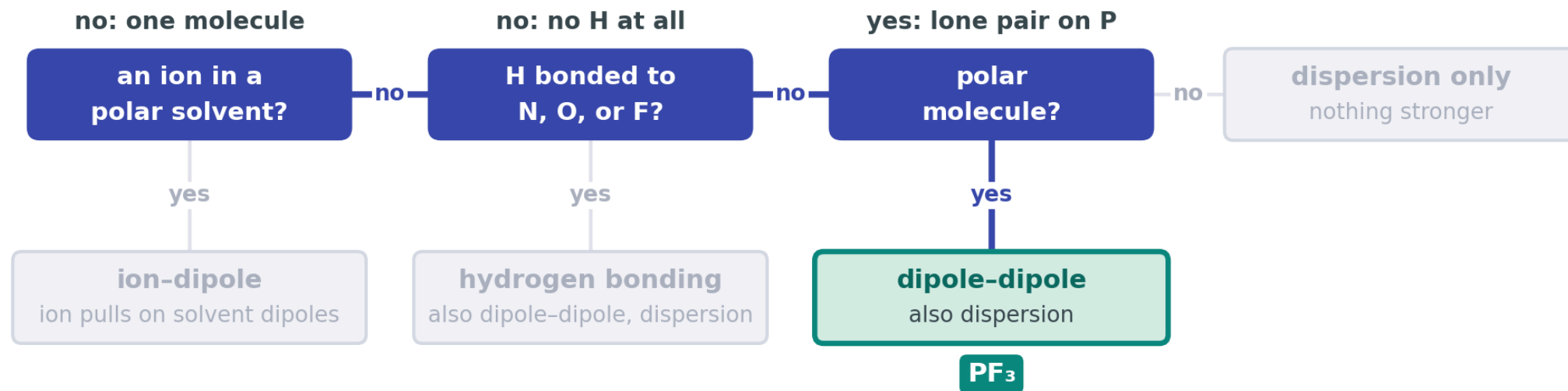
B treated PF_3 like BF_3 : the lone pair on P makes it pyramidal, so the three P-F dipoles do not cancel. C left out dispersion, which every substance has. D counted the F as a hydrogen-bond trigger, but PF_3 has no H at all.



Sense check: Two forces are present, and dipole-dipole is the stronger of them. ✓

✓ Practice 3: the route on the chart

$\text{PF}_3 \rightarrow$ dispersion + dipole-dipole · answer A
a molecule, no ion · no H at all · lone pair on P $\rightarrow$ polar



Sense check: No, no, yes: PF_3 exits at dipole-dipole. Fluorine alone is not a yes at the second question; the H must be bonded to it. ✓



Practice 4



carbon dioxide · difluoromethane · hydrazine · ethane

Which substance has dipole–dipole forces as its strongest intermolecular force?

- A. CO_2
- B. CH_2F_2
- C. N_2H_4
- D. C_2H_6

✓ Practice 4 answer: B

$\text{CH}_2\text{F}_2 \rightarrow$ strongest force: dipole-dipole · answer B

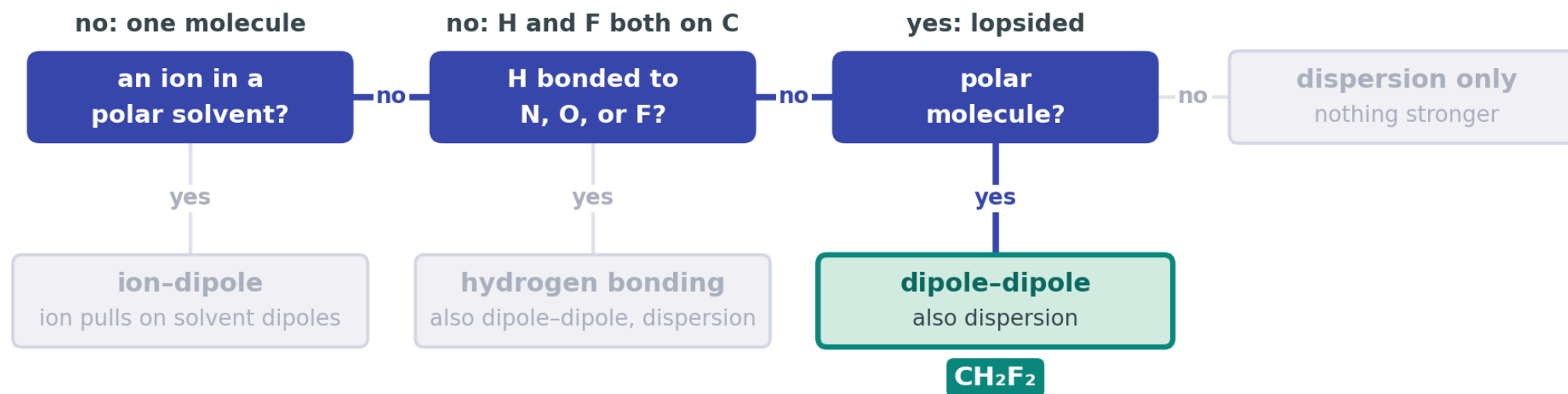
no ion · both H and both F bonded to C, so no H on F · two H and two F around carbon $\rightarrow$ polar

A has polar C=O bonds, but $\text{O}=\text{C}=\text{O}$ is linear with matching ends: the dipoles cancel, leaving dispersion only. C is polar, but each H sits on N, so hydrogen bonding outranks dipole-dipole. D counted C-H as a polar bond; ethane is nonpolar, with dispersion only.

 **Sense check:** Only CH_2F_2 is polar with no H on N, O, or F. ✓

✓ Practice 4: the route on the chart

$\text{CH}_2\text{F}_2 \rightarrow$ strongest force: dipole-dipole · answer B
a molecule, no ion · H and F both bonded to C · lopsided $\rightarrow$ polar



🧠 **Sense check:** CH_2F_2 holds fluorine, yet no H is bonded to F. Its first yes is polarity, so it exits at dipole-dipole. ✓



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

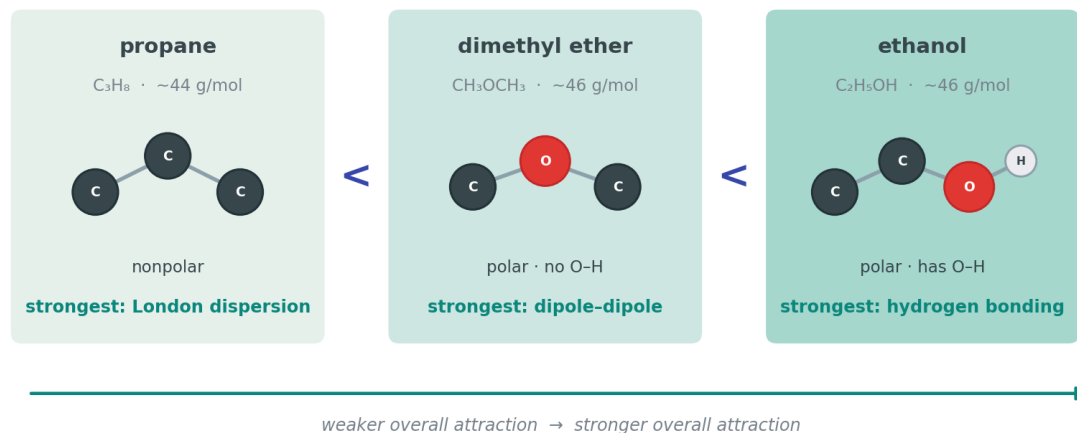
 **Sense check:** Each one has dispersion. The polar ether adds dipole-dipole; ethanol's O-H adds hydrogen bonding on top.

✓ 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

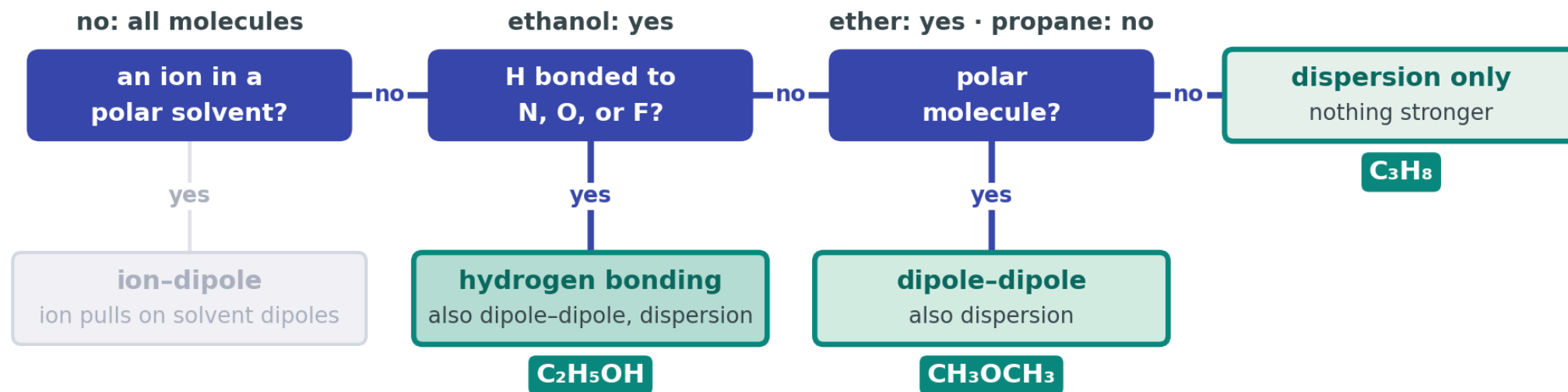


 **Sense check:** Similar masses, so the strongest-force type sets the order: propane < dimethyl ether < ethanol.

✓ 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 5

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 5 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

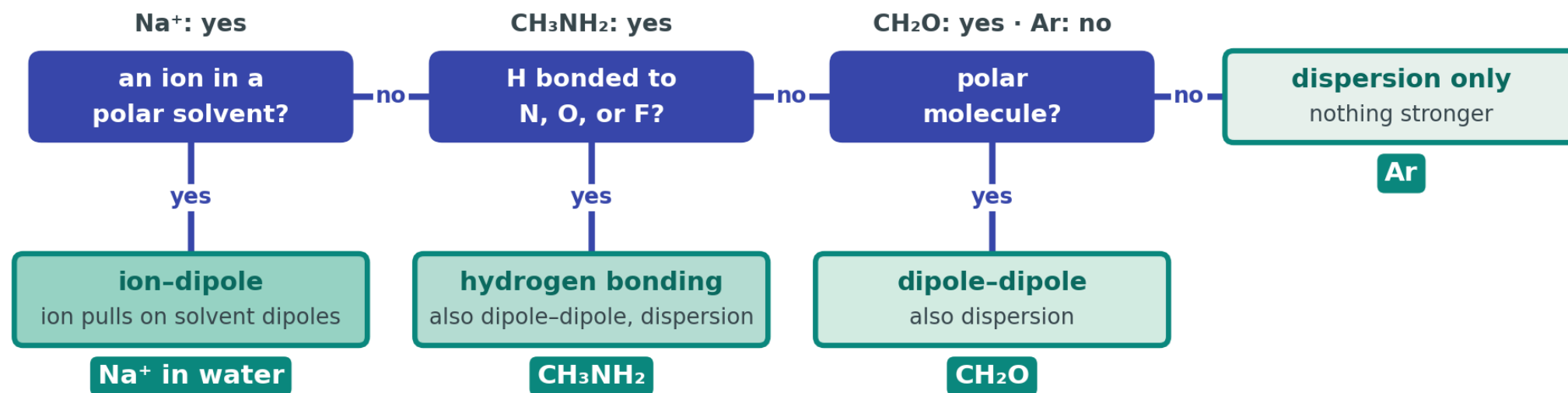
Argon is a lone nonpolar atom: dispersion only. CH_2O is polar, but both H atoms sit on carbon: dipole-dipole. CH_3NH_2 has H on N: hydrogen bonding. Na^+ pulls on water's dipoles: ion-dipole.

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 5: the route on the chart

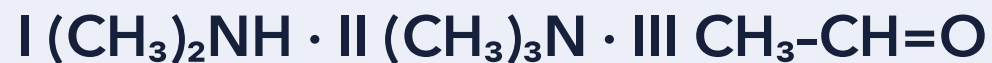
$\text{Ar} < \text{CH}_2\text{O} < \text{CH}_3\text{NH}_2 < \text{Na}^+$ in water · answer D
dispersion only · dipole-dipole · hydrogen bonding · ion-dipole



🧠 **Sense check:** Four substances leave by four exits. Read the exits from right to left for the ranking, weakest first. ✓



Practice 6



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 6 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 7

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 7 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 8



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 8 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.

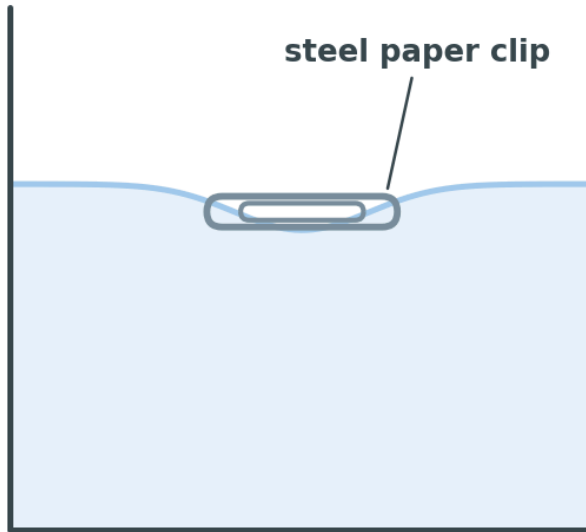
2 · Properties of Liquids

Explain surface tension, viscosity, capillary action, and vapor pressure from the strength of a liquid's intermolecular forces, read a boiling point at any outside pressure from a vapor-pressure curve, and predict which of two liquids shows more of each.

A paper clip on water

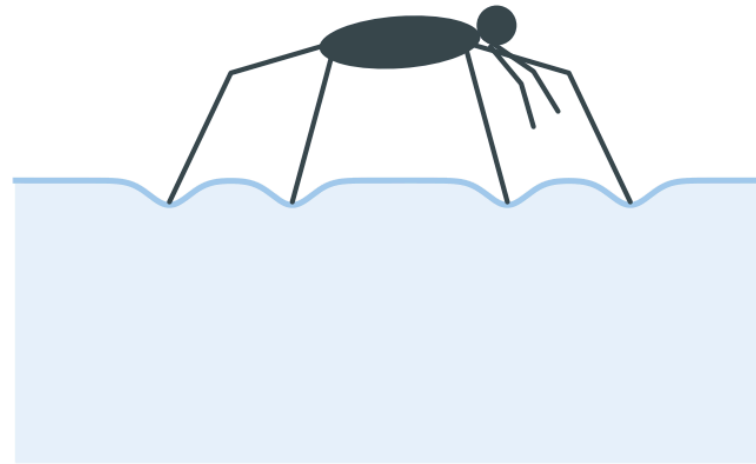
A liquid surface can carry weight

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.

Gasoline and motor oil

gasoline: chains of 4 to 12 carbons · motor oil: chains of 20 to 50 carbons
both nonpolar: dispersion forces only

Gasoline pours thin, and a spill evaporates in minutes. Motor oil pours slowly, and a drip lasts for weeks. Which one's molecules hold each other more tightly?

Motor oil: its long chains touch more and tangle.

longer chains → stronger dispersion → tighter hold
tighter hold: slower flow and slower escape

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

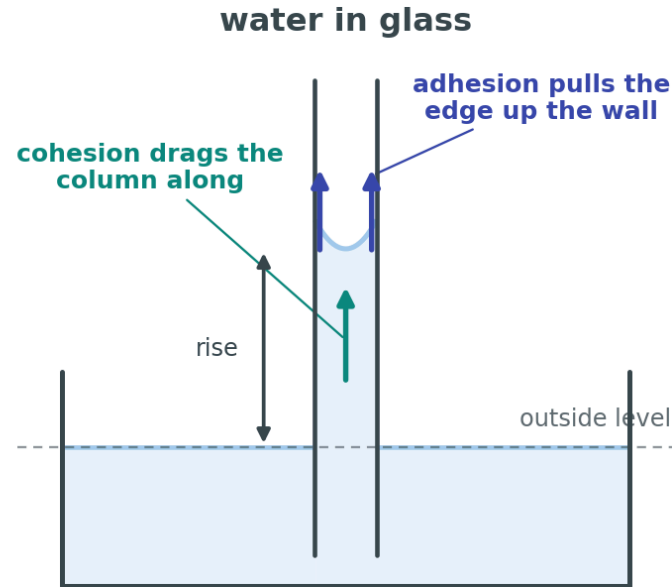
Flow makes molecules slide past their neighbors. Anything that holds neighbors together slows the slide: stronger forces, longer molecules with more contact, lower temperature.

viscosity rises with stronger forces · longer chains · lower temperature

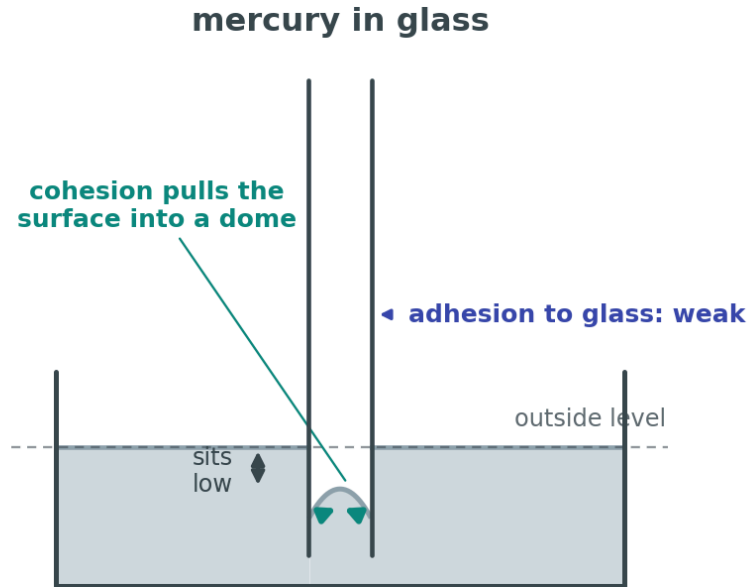
$\text{C}_5\text{H}_{12} < \text{C}_6\text{H}_{14} < \text{C}_7\text{H}_{16}$ in viscosity · warming a liquid always thins it

Capillary action and the meniscus

The stronger attraction sets the meniscus



adhesion beats cohesion: climbs, concave meniscus

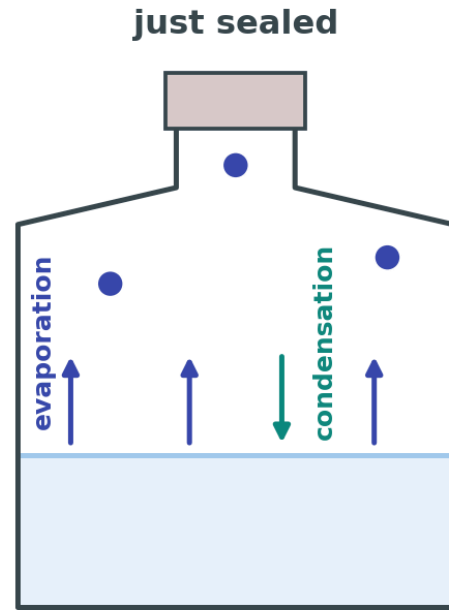


cohesion beats adhesion: stays low, convex meniscus

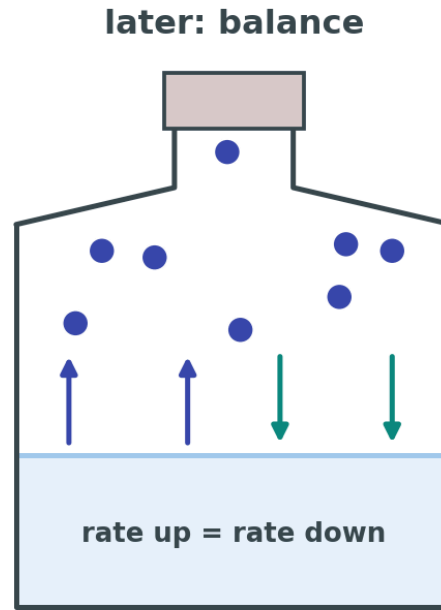
Adhesion pulls water up the glass wall and cohesion drags the column along: water climbs, surface dipping in the middle. Mercury coheres more than it adheres to glass: it bulges and stays low.

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.

Boiling: vapor pressure meets outside pressure

Vapor pressure climbs as a liquid warms. When it matches the external pressure above the liquid, vapor bubbles form throughout and the liquid boils. At exactly 1 atm, this is the normal boiling point.

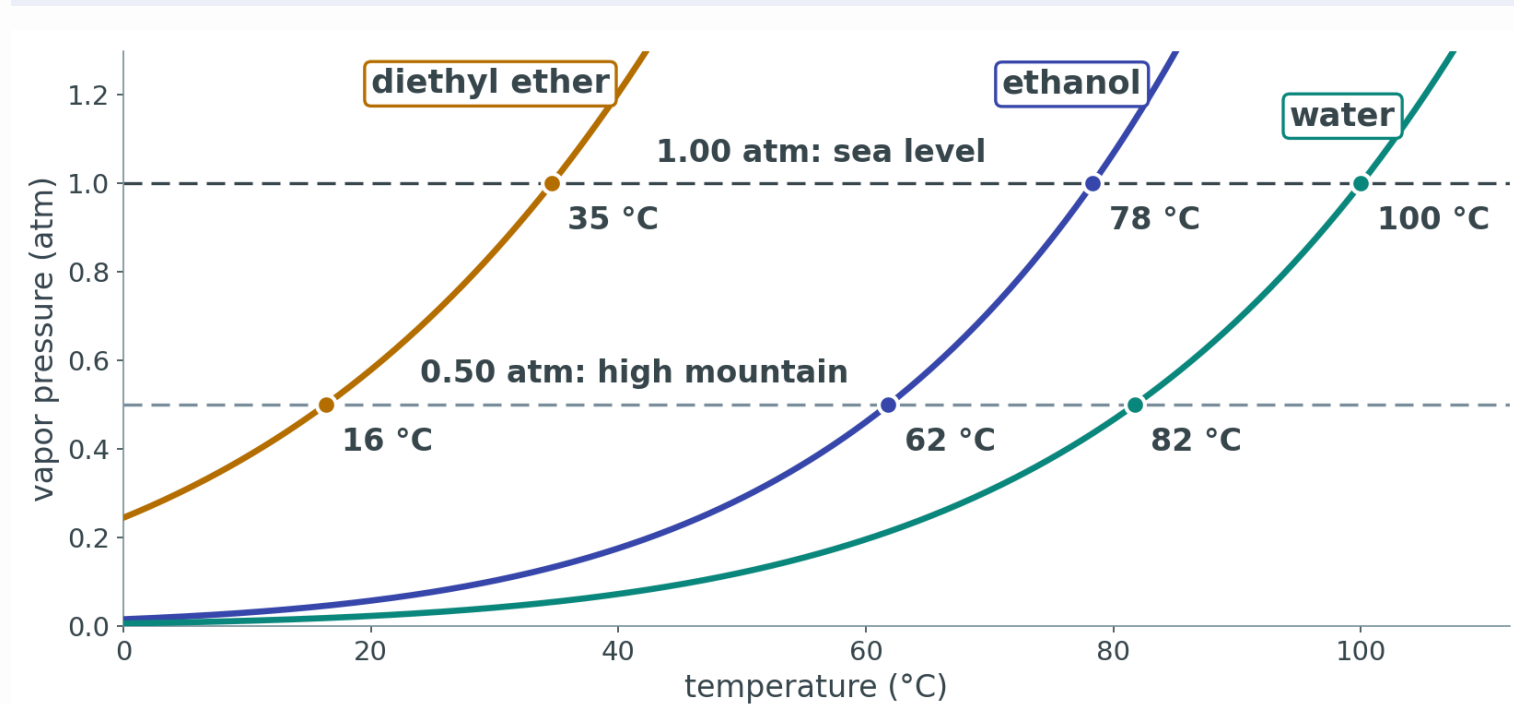
boils when vapor pressure = external pressure

high mountain: less pressure above → boils cooler · pressure cooker: more pressure above → boils hotter

memory hook: boiling is a pressure match, not a fixed temperature

water: 100 °C at 1 atm · near 82 °C at 0.50 atm · near 120 °C at 2 atm, inside a pressure cooker

Reading a vapor-pressure curve



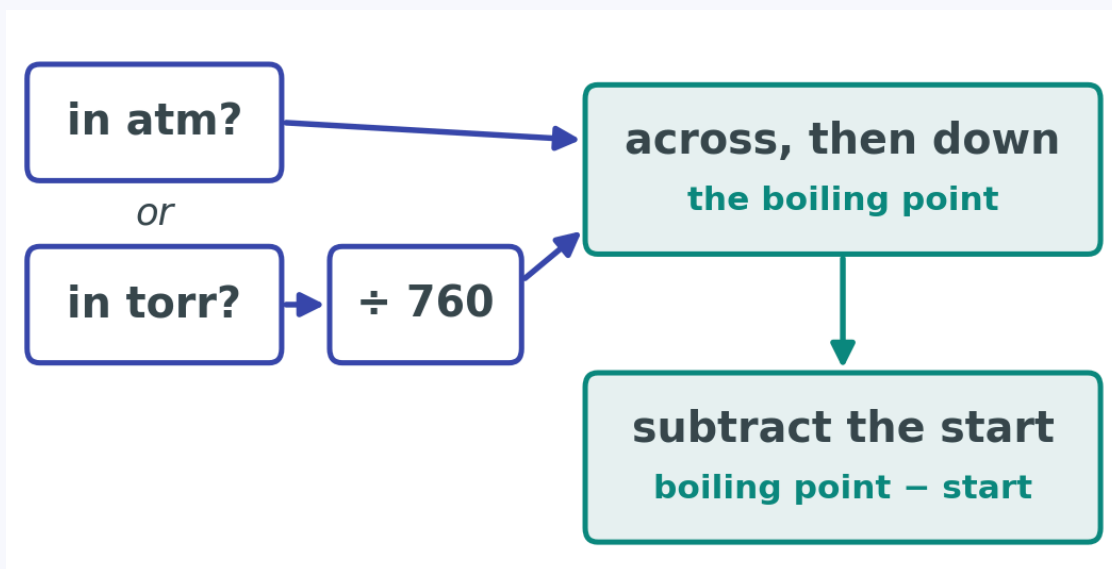
A liquid boils where its curve meets the outside-pressure line. On a mountain at 0.50 atm, water boils at 82 °C, so pasta cooks slower.

read across at the outside pressure, then down to the temperature
1.00 atm: ether 35 °C · ethanol 78 °C · water 100 °C · weakest forces, lowest boiling point



The method: boiling at an outside pressure

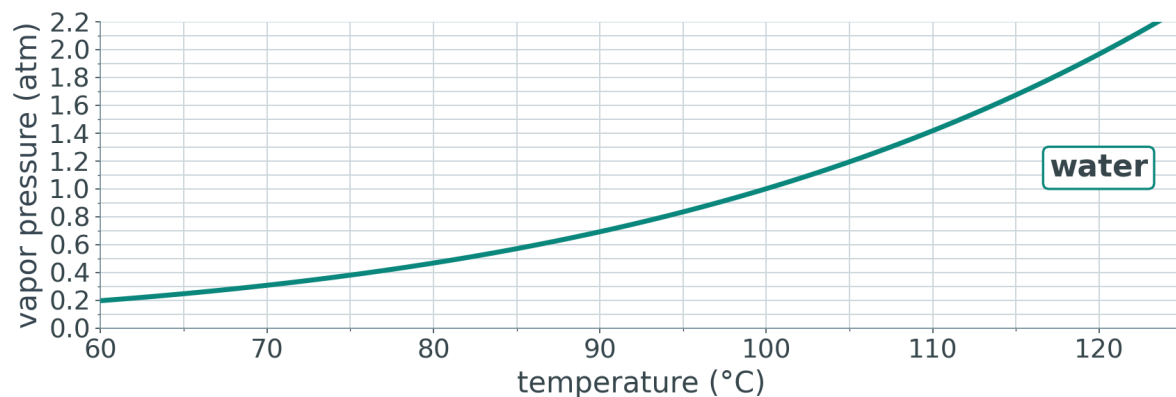
1. **Put the outside pressure in atm.** 760 torr = 1 atm.
2. **Read across, then down.** Across to the curve, down to the boiling point.
3. **Subtract the starting temperature.** The difference is the warming.



Guided example: water on a mountain

a mountain camp near 4,500 m

given: outside pressure 0.57 atm · water starts at 20 °C · wanted: boiling point, warming before it boils



Climbers heat a pot of water from **20 °C** where the air presses at **0.57 atm**. At what temperature does it boil, and how many degrees does it warm first?

Read the curve at the camp's pressure, not at 1 atm.

✓ Guided example: solution

a mountain camp near 4,500 m

given: outside pressure 0.57 atm · water starts at 20 °C · wanted: boiling point, warming before it boils

Step 1 · Put the outside pressure in atm

Step 2 · Read across, then down

0.57 atm → across to water's curve → down to **85 °C**

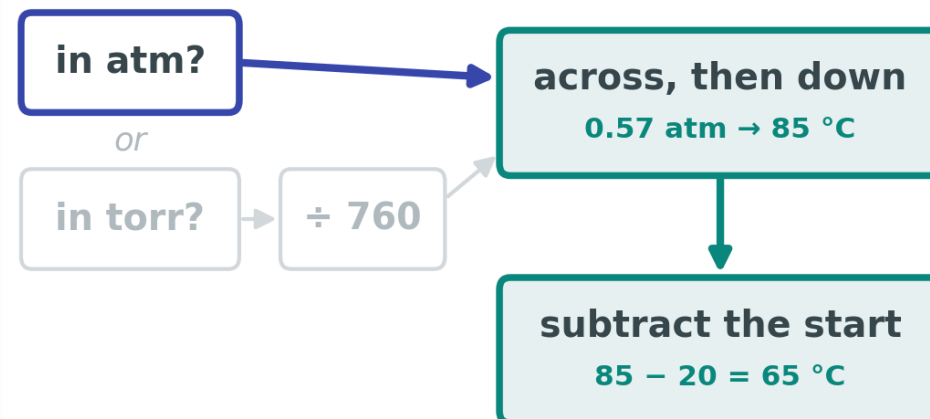
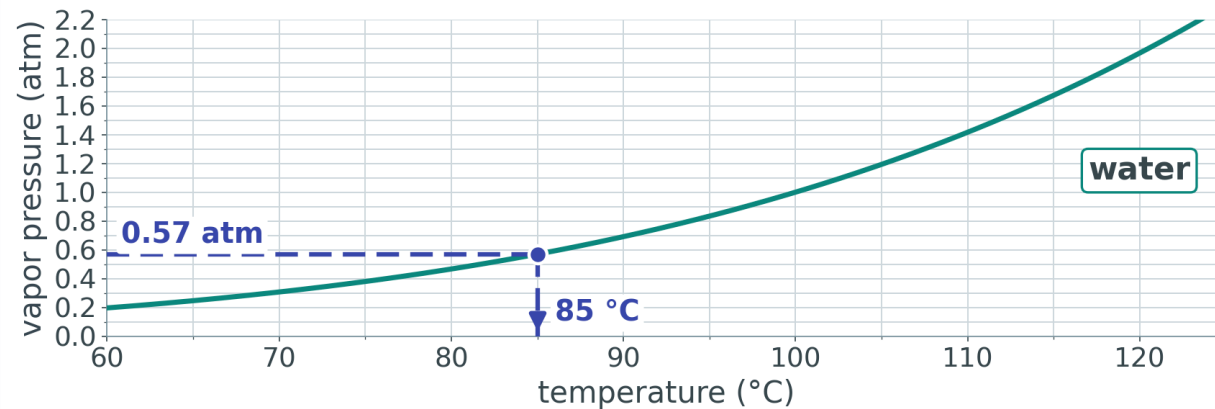
Step 3 · Subtract the starting temperature

$85\text{ °C} - 20\text{ °C} = \mathbf{65\text{ °C}}$ of warming before it boils

 **Sense check:** Water boils 15 °C below its normal 100 °C at this camp, so the pot warms 65 °C, not 80 °C. The cooler boiling water cooks food more slowly. ✓

✓ Guided example: the route on the map

given: 0.57 atm · water starts at 20 °C
found: boils at 85 °C · warms 65 °C before it boils

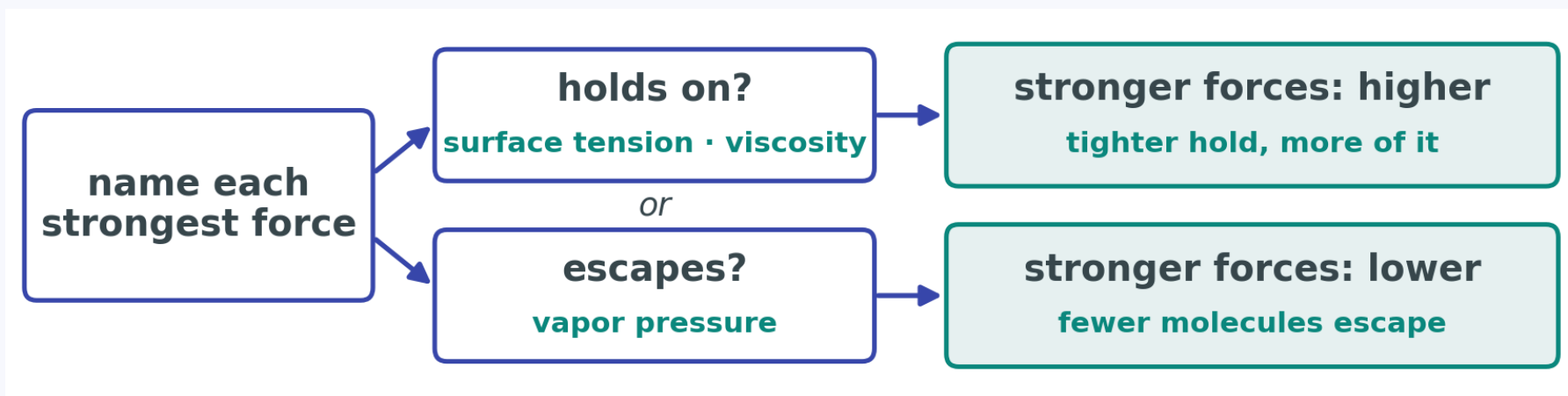


🧠 **Sense check:** The pressure came in atm, so the $\div 760$ branch stays dark: read the curve, then subtract the start. ✓



The method: comparing two liquids

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

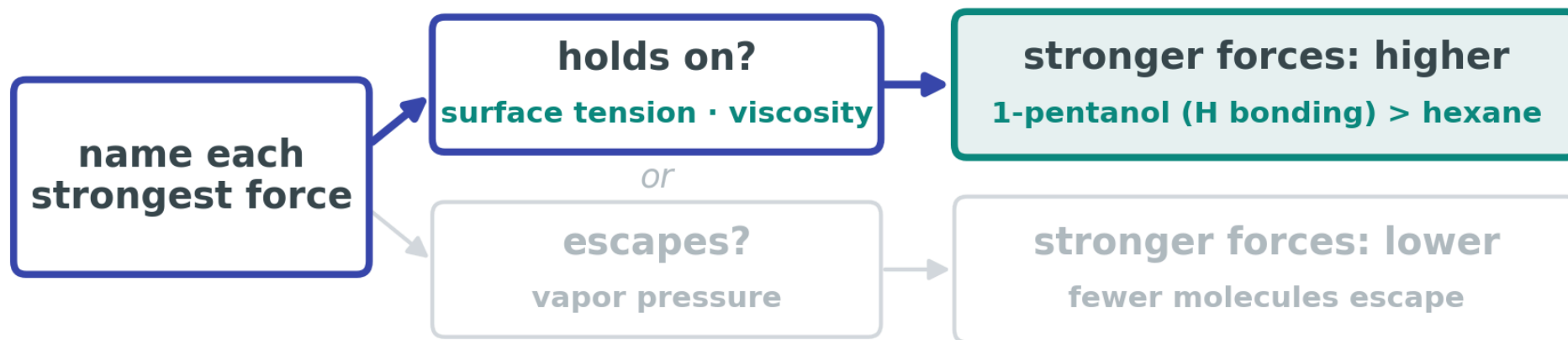
Step 3 · Stronger forces hold tighter

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 °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

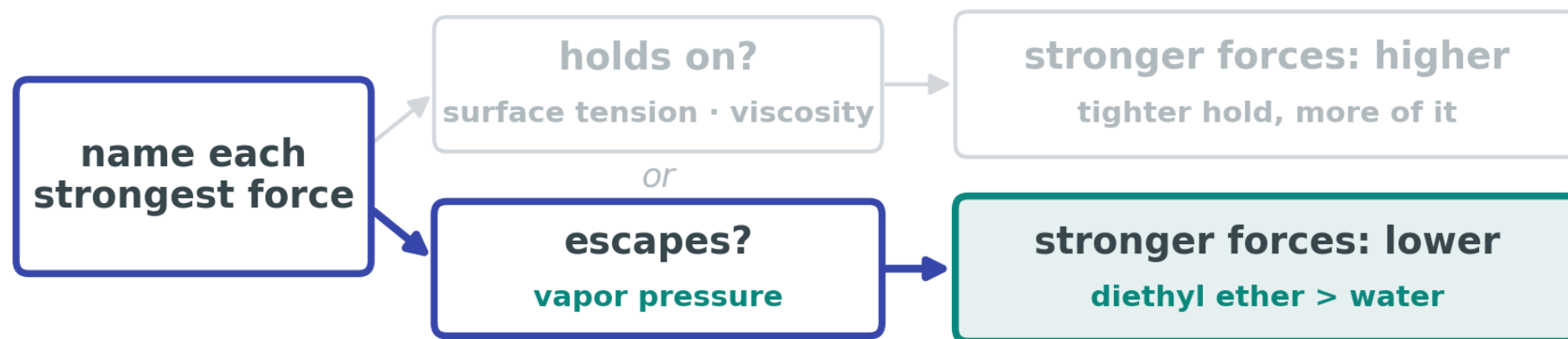
ether: weaker forces → more molecules escape

→ **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: boiling below sea level

the floor of Death Valley: 86 m below sea level
at sea level: 1.00 atm · water's normal boiling point: 100 °C

How does water's boiling point on the valley floor compare with 100 °C?

- A. Lower: the air pressure there is below 1 atm
- B. The same: water always boils at 100 °C
- C. Higher: the air pressure there is above 1 atm
- D. Higher: water's hydrogen bonds are stronger there

✓ Practice 1 answer: C

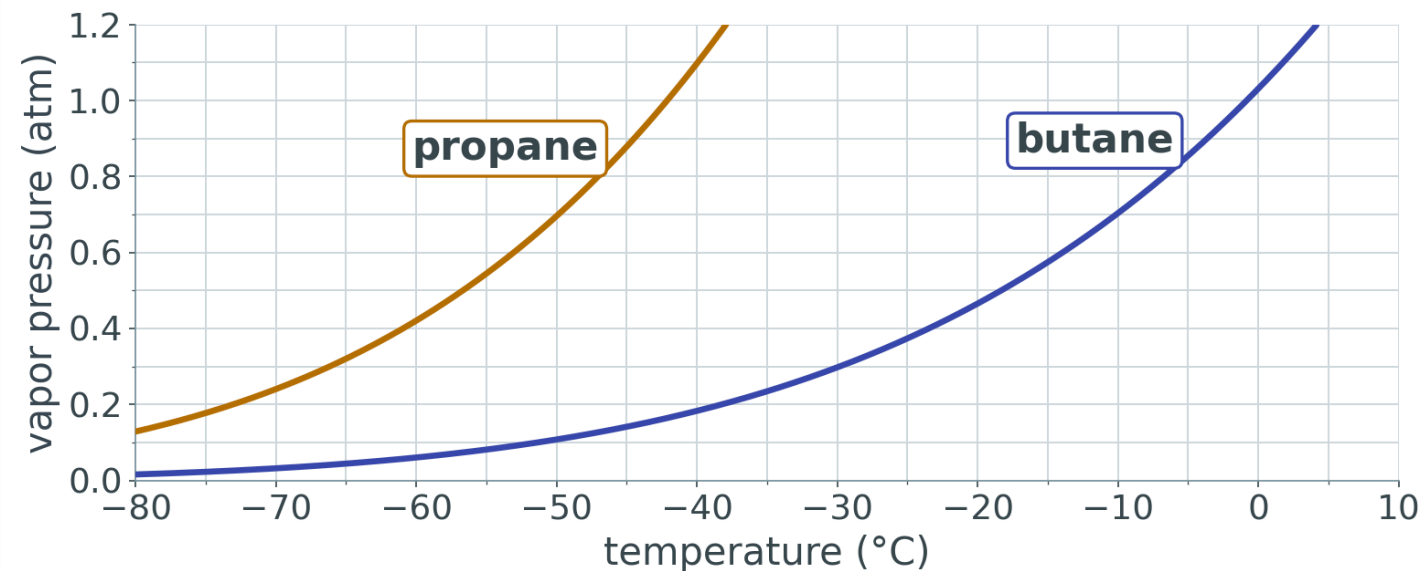
below sea level → more air above → outside pressure above 1 atm → boils above 100 °C · answer C

boils when vapor pressure = outside pressure · about 1.01 atm on the valley floor · water boils near 100.3 °C

A reversed the direction: air pressure falls going up a mountain and rises going below sea level. B treated the boiling point as fixed; 100 °C holds only at exactly 1 atm. D changed the forces; water's hydrogen bonds are the same everywhere, and only the pressure it must match changes.

🧠 **Sense check:** 86 m adds only a little air, so water boils only slightly above 100 °C. More pressure above, hotter boil. ✓

Practice 2: reading a vapor-pressure curve



From the curves, what are propane's normal boiling point and its boiling point at 0.40 atm, in °C?

- A. normal -42, at 0.40 atm -61
- B. normal -61, at 0.40 atm -42

- C. normal -42, at 0.40 atm -42
- D. normal -1, at 0.40 atm -23

✓ Practice 2 answer: A

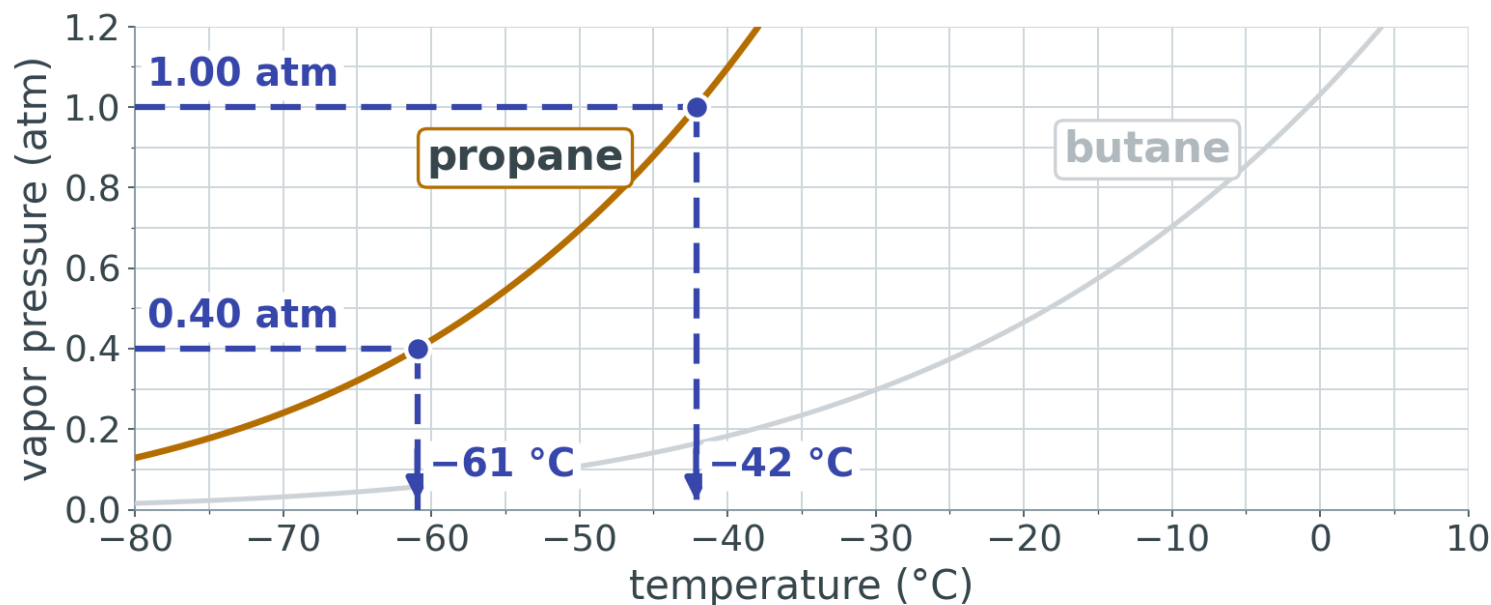
1.00 atm line meets propane at $-42\text{ }^{\circ}\text{C}$ · 0.40 atm line meets it at $-61\text{ }^{\circ}\text{C}$ · answer A read across at the outside pressure, then down to the temperature · less pressure above → boils cooler

B swaps the reads: a lower outside pressure pairs with the lower temperature, never the higher one. C read the 1.00 atm line twice, as if a boiling point were fixed. D read butane's curve, the one on the right.

🧠 **Sense check:** Propane boils $19\text{ }^{\circ}\text{C}$ cooler at 0.40 atm, the same direction as water on a mountain. ✓

✓ Practice 2: the route on the curve

propane: across at 1.00 atm, down to $-42\text{ }^{\circ}\text{C}$ · across at 0.40 atm, down to $-61\text{ }^{\circ}\text{C}$
 both pressures given in atm · no starting temperature, so nothing to subtract



🧠 **Sense check:** Two reads on one curve. The lower outside pressure meets propane's curve at the cooler temperature. ✓



Practice 3

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 3 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 4

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 4 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.

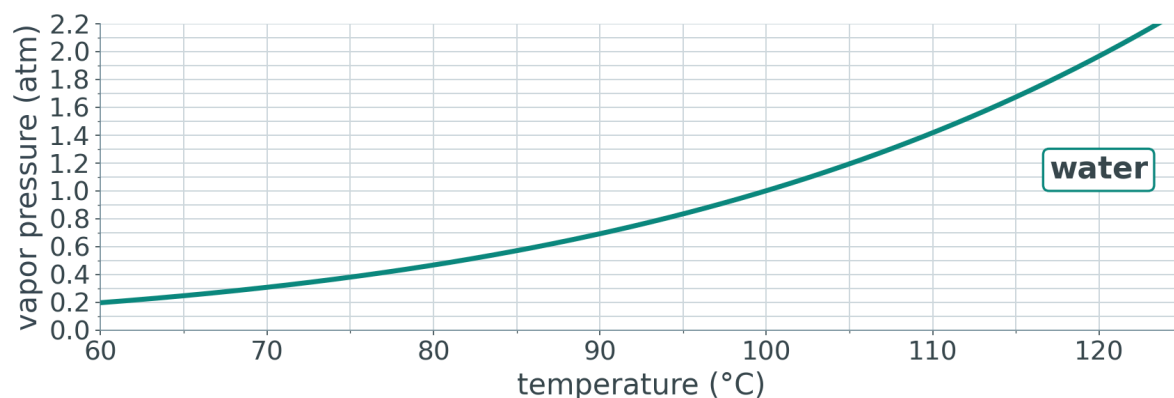
 **Sense check:** Strong forces hold, weak forces let go. Vapor pressure climbs from the hydrogen-bonded liquid to the dispersion-only one.



Practice 5: inside a pressure cooker

a sealed pressure cooker on the stove

given: 1270 torr above the water · water at 22 °C when the lid locks



The lid keeps **1270 torr** over water that starts at **22 °C**. By how many degrees Celsius does it warm before it boils?

A. 115

B. 78

C. 100

D. 93

✓ Practice 5 answer: D

pressure cooker: 1270 torr above the water · water starts at 22 °C
three moves: torr to atm · read the curve · subtract the start

$$1270 \text{ torr} \times \frac{1 \text{ atm}}{760 \text{ torr}} = 1.67 \text{ atm} \rightarrow \text{curve: boils at } 115 \text{ }^{\circ}\text{C}$$

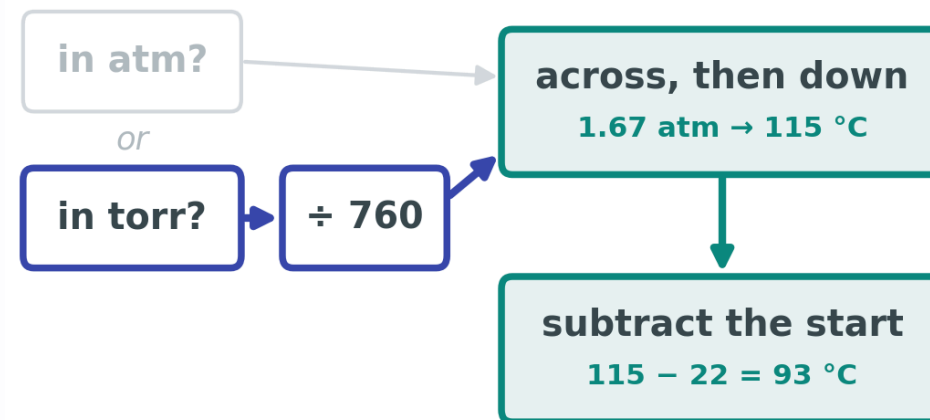
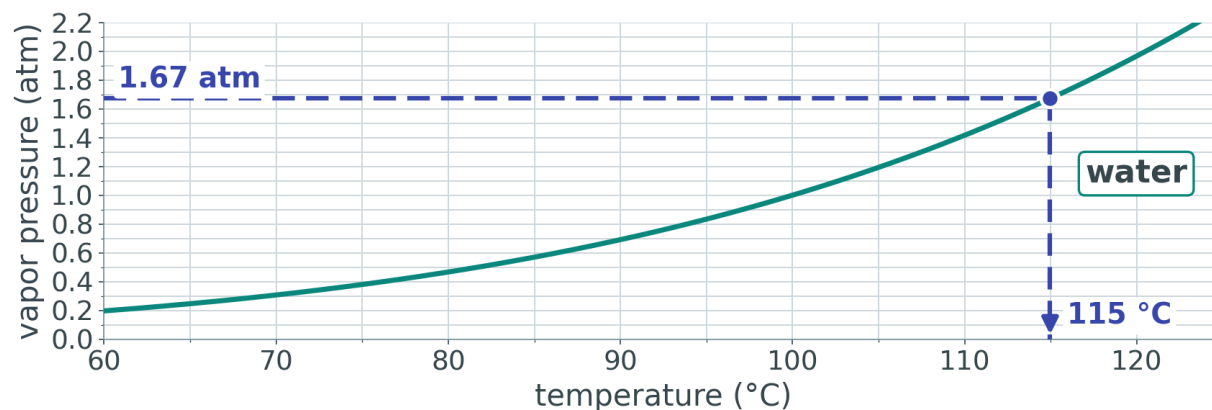
$$115 \text{ }^{\circ}\text{C} - 22 \text{ }^{\circ}\text{C} = \mathbf{93 \text{ }^{\circ}\text{C of warming (answer D)}}$$

🧠 **Sense check:** More pressure above, hotter boil: 115 °C instead of 100 °C, so food cooks faster. ✓

✓ Practice 5: the route on the map

given: 1270 torr · water starts at 22 °C

found: 1.67 atm · boils at 115 °C · warms 93 °C before it boils



🧠 **Sense check:** The pressure came in torr, so this route runs through $\div 760$ before the curve, then subtracts the start.





Practice 6

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 6 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.

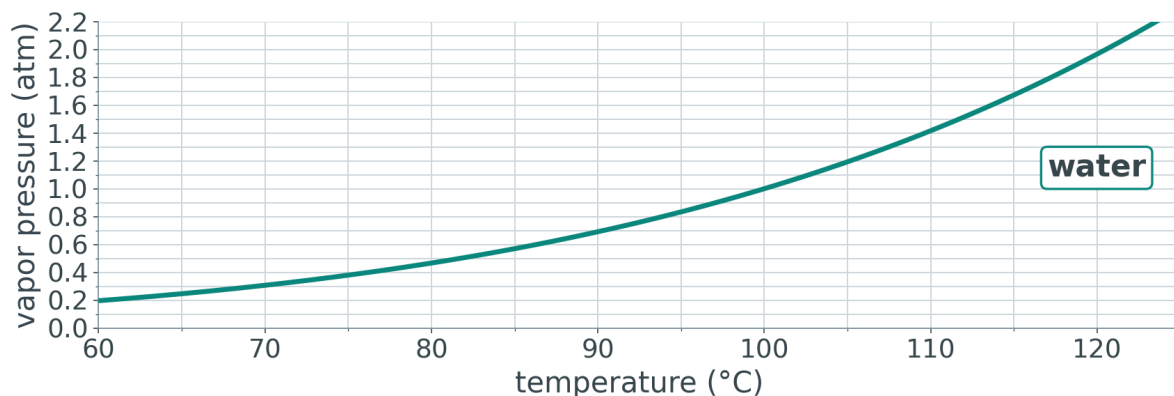
A raised all three; stronger forces lower vapor pressure. B reversed the ranking; hydrogen bonding outranks dipole-dipole. D let the shared formula decide, or counted the ether's O as hydrogen bonding; that needs an H on the O.

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



Practice 7: boiling in a mountain city

a kitchen in a city near 1,500 m
given: 0.83 atm outside · tap water at 16 °C



Tap water at **16 °C** goes on the stove in a city where the outside pressure is **0.83 atm**. By how many degrees Celsius does it warm before it boils?

A. 79

B. 95

C. 100

D. 84

✓ Practice 7 answer: A

a city near 1,500 m: 0.83 atm outside · tap water at 16 °C
the pressure is already in atm · read the curve · subtract the start

0.83 atm → across to water's curve → down to 95 °C

$95\text{ °C} - 16\text{ °C} = 79\text{ °C of warming (answer A)}$

🧠 **Sense check:** Less pressure above, cooler boil: 95 °C instead of 100 °C, so pasta in this city cooks a little slower. ✓



Practice 8

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 8 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

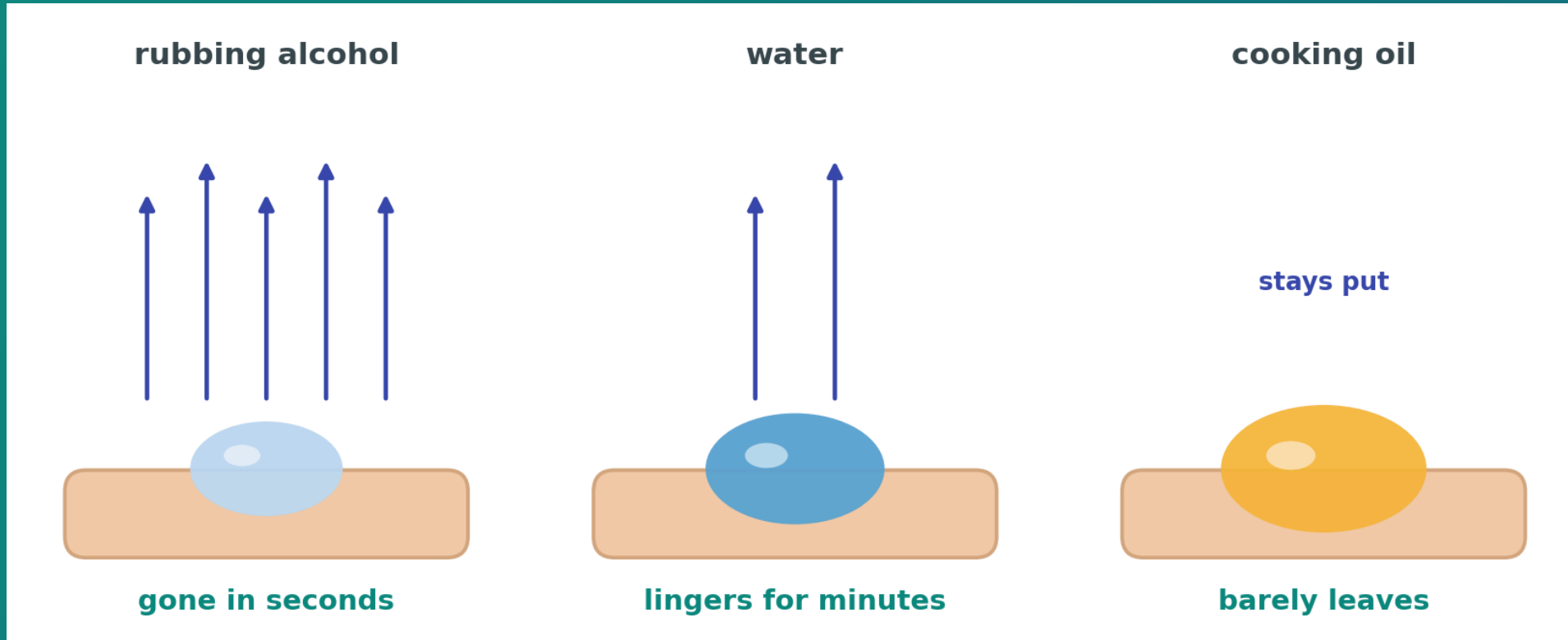
1. Glycerol's molecules each carry three O-H groups; acetone's carry none. Which liquid is more viscous at room temperature, and why?
2. A sealed flask of water sits at a steady vapor pressure. Name the two processes still running at the liquid surface and compare their rates.

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

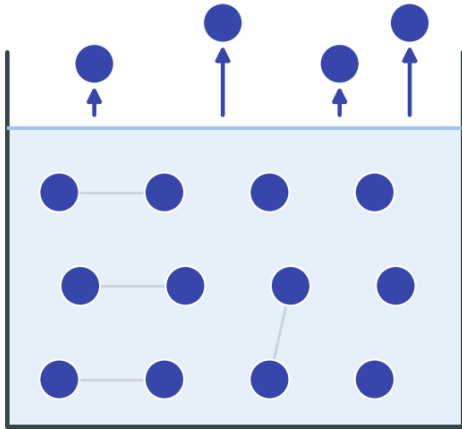


Rubbing alcohol dries in seconds. Water lingers for minutes. Cooking oil barely leaves at all. Stronger attractions between molecules hold a liquid together longer.

Boiling pulls molecules apart

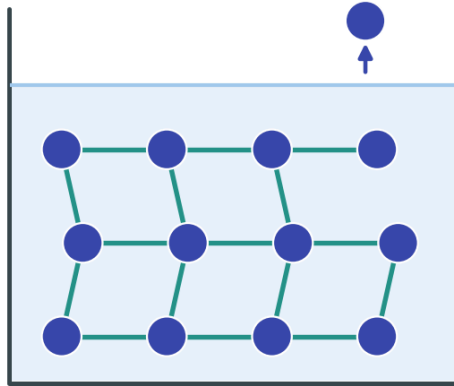
Boiling means pulling the molecules apart

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

Boiling points compare the forces

water boils at 100 °C · rubbing alcohol boils at 82 °C
both at 1 atm · to boil, molecules must pull free of their neighbors

Which liquid's molecules attract each other more strongly?

Water. It must be heated 18 °C further before its molecules break free. A higher boiling point means stronger intermolecular forces.

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.

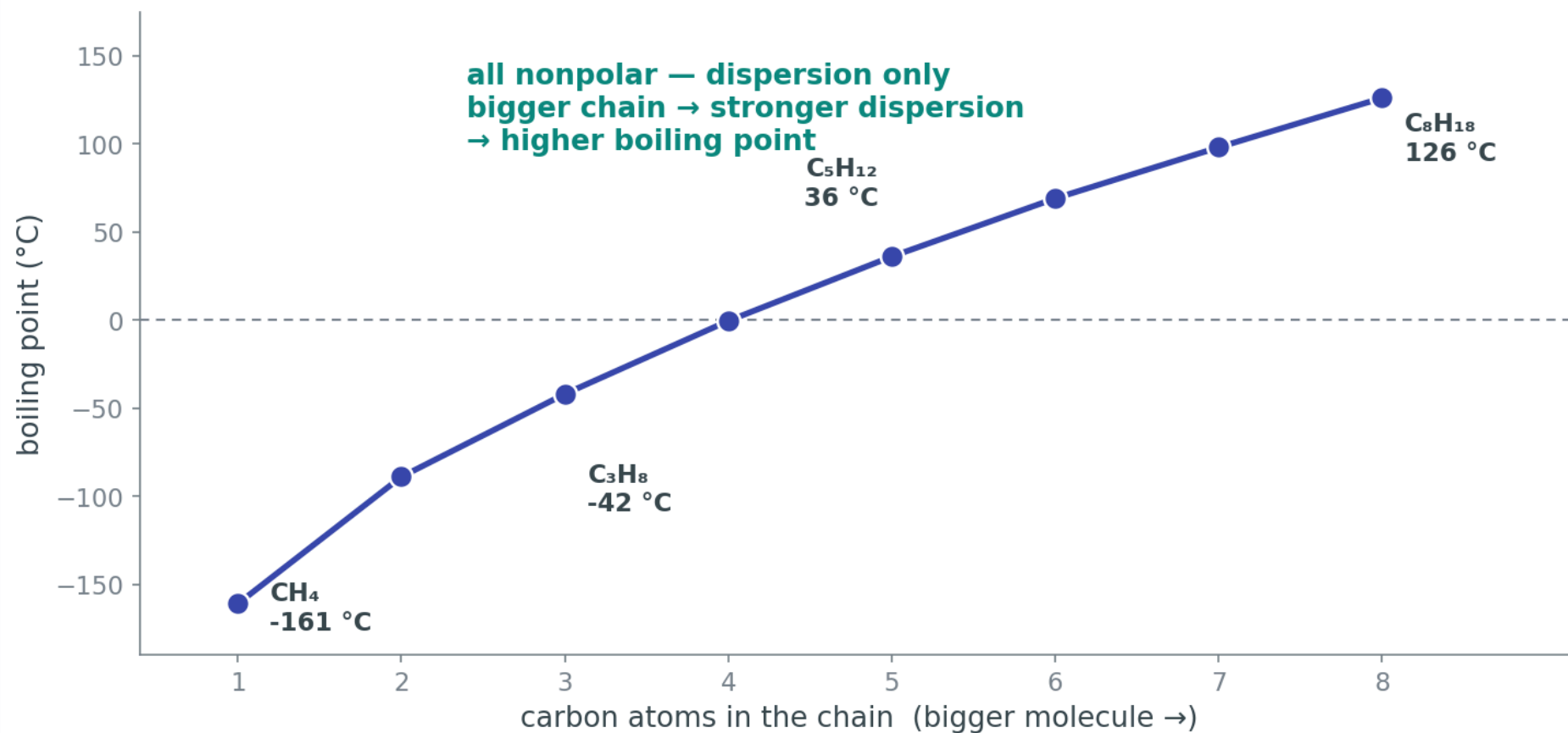
at $\approx 44\text{-}46$ g/mol: ethanol (hydrogen bonding) 78°C · dimethyl ether (dipole-dipole) -24°C · propane (dispersion) -42°C

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

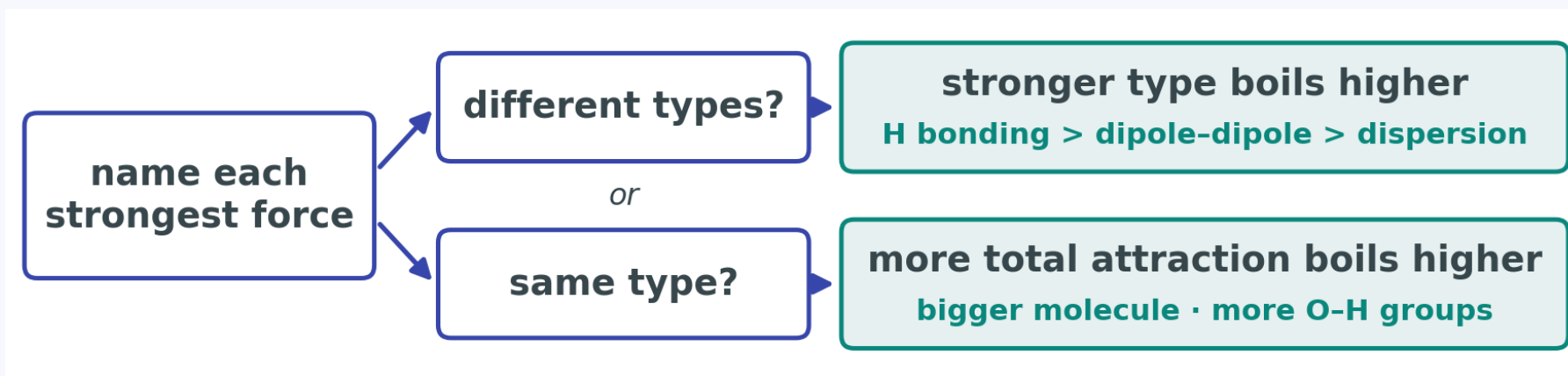


Nonpolar molecules have only dispersion forces. Dispersion comes from the electrons, so a bigger molecule with more electrons and more surface attracts more strongly.



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.





Guided example: nitrogen and carbon monoxide

nitrogen (N_2) vs carbon monoxide (CO)

N_2 28.02 g/mol · CO 28.01 g/mol · wanted: which boils higher, and why

Two gases with the same molar mass, so dispersion is the same for both. Nitrogen joins two identical atoms; carbon monoxide joins two different ones.

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

✓ Guided example: solution

nitrogen (N_2) vs carbon monoxide (CO)

N_2 28.02 g/mol · CO 28.01 g/mol

Step 1 · Identify each substance's strongest force

Step 2 · The stronger force boils higher

CO $-191.5\text{ }^\circ\text{C}$ · N_2 $-195.8\text{ }^\circ\text{C}$

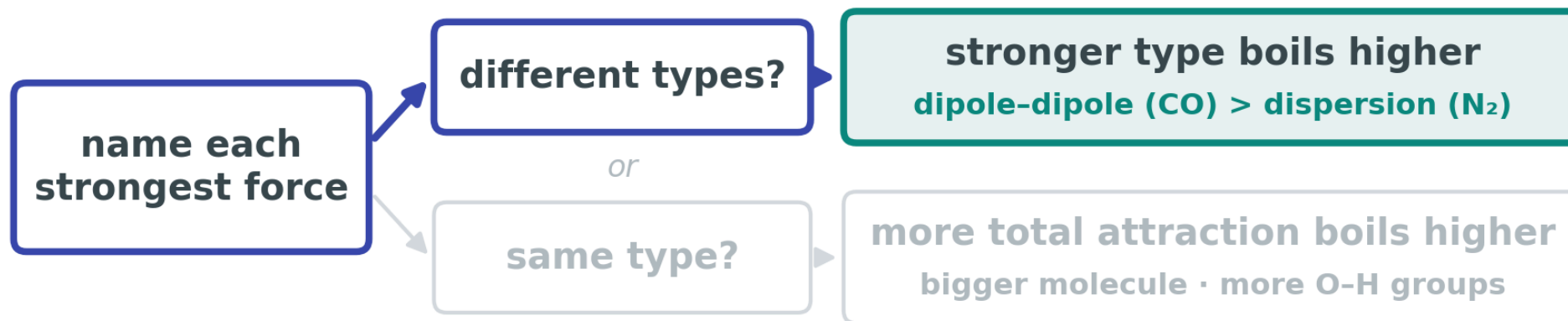
dipole-dipole vs dispersion · 28.01 vs 28.02 g/mol

🧠 **Sense check:** CO boils $4.3\text{ }^\circ\text{C}$ higher. A weak dipole gives a small lift, but the order follows the force type. ✓

✓ Guided example: the route on the map

nitrogen (N_2) vs carbon monoxide (CO)

given: 28.02 vs 28.01 g/mol · found: CO boils higher, $-191.5\text{ }^\circ\text{C}$ vs $-195.8\text{ }^\circ\text{C}$



🧠 **Sense check:** Two different force types, so only the top row was used. The masses match, so size never entered. ✓



Practice 1

hydrogen fluoride (HF) vs hydrogen chloride (HCl)

HF 20.01 g/mol · HCl 36.46 g/mol · both polar molecules

Which has the higher boiling point?

- A. HCl: the heavier molecule has more dispersion
- B. HF: its H on F adds hydrogen bonding
- C. Neither: both are polar, so they boil near the same temperature
- D. HCl: its H on Cl adds hydrogen bonding

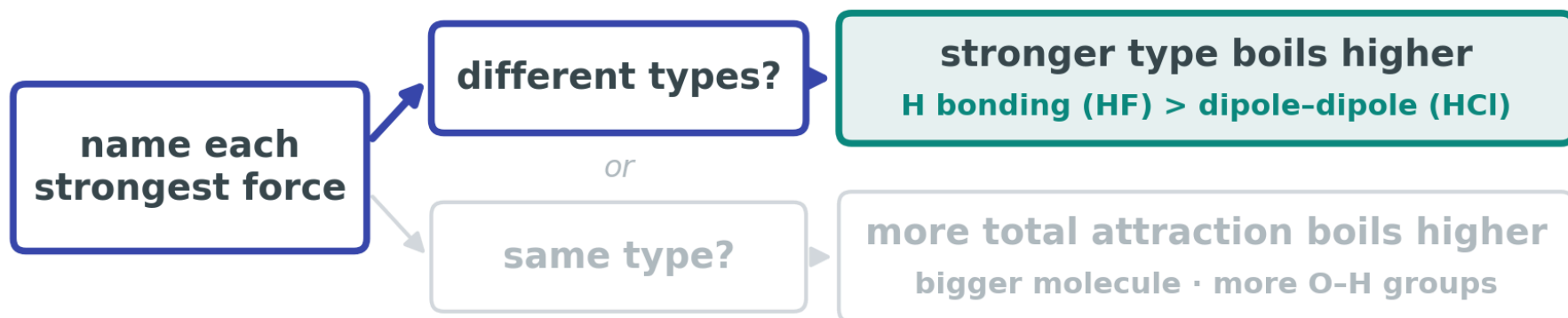
✓ Practice 1 answer: B

HF: hydrogen bonding · HCl: dipole-dipole · answer B

H on F qualifies · H on Cl does not · HF 20 °C vs HCl –85 °C

🧠 **Sense check:** HF boils 105 °C above HCl at about half its mass. Type first. ✓

The route on the map





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

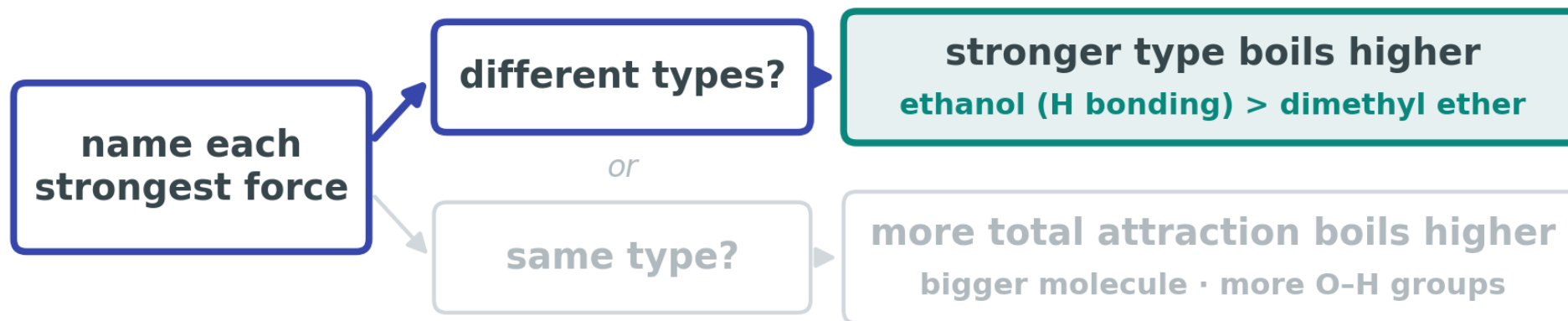
ethanol 78 °C · dimethyl ether –24 °C

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

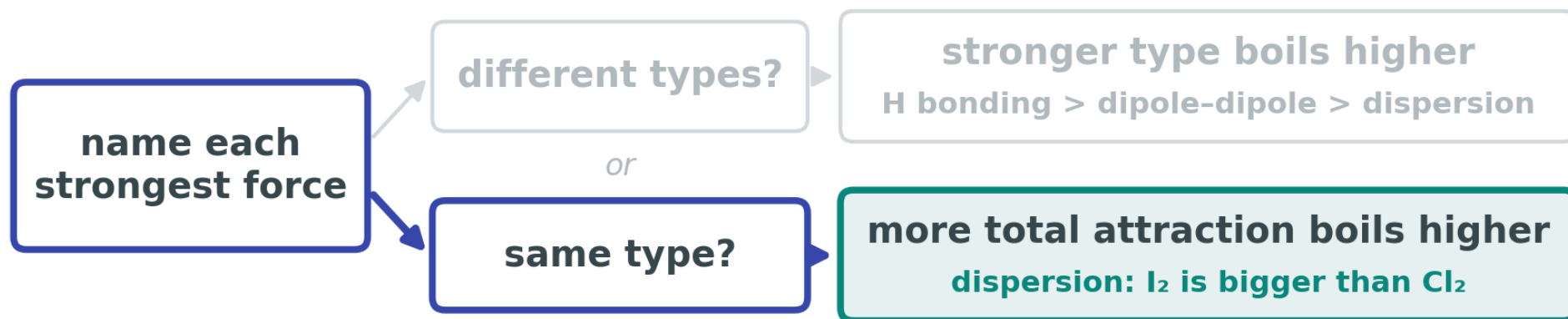
253.80 g/mol vs 70.90 g/mol · dispersion grows with size

🧠 **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

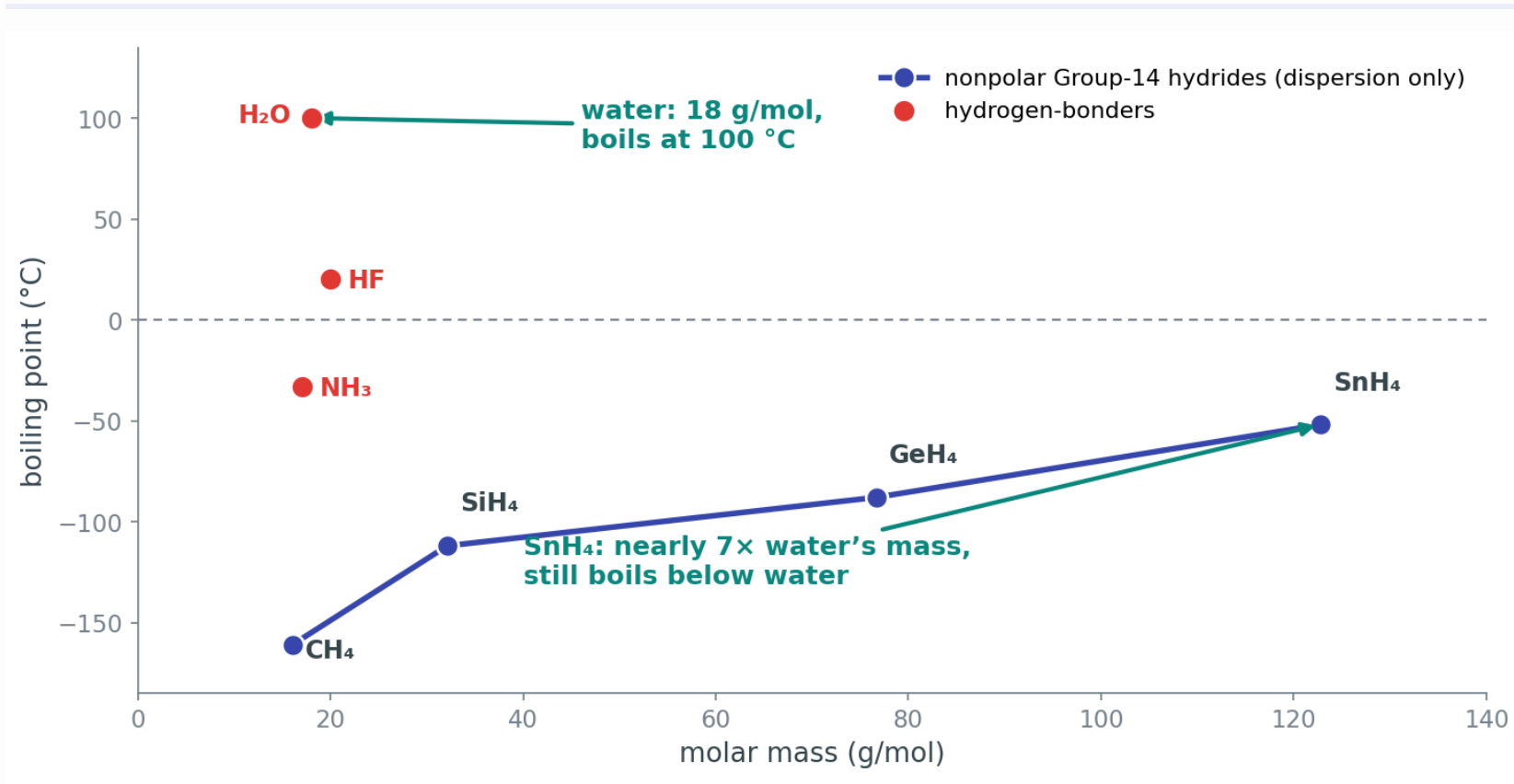
chlorine (Cl_2) vs iodine (I_2)

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 2

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.

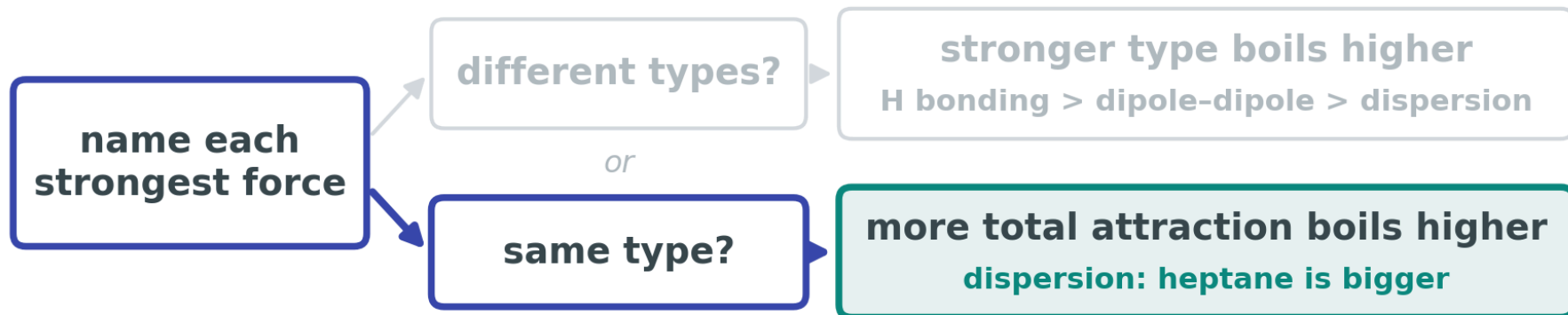
✓ Practice 2 answer: A

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

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

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

The route on the map





Practice 3

hydrogen chloride (HCl) vs hydrogen bromide (HBr)

HCl 36.46 g/mol · HBr 80.91 g/mol · both polar · HCl is the more polar molecule

Which boils higher, and why?

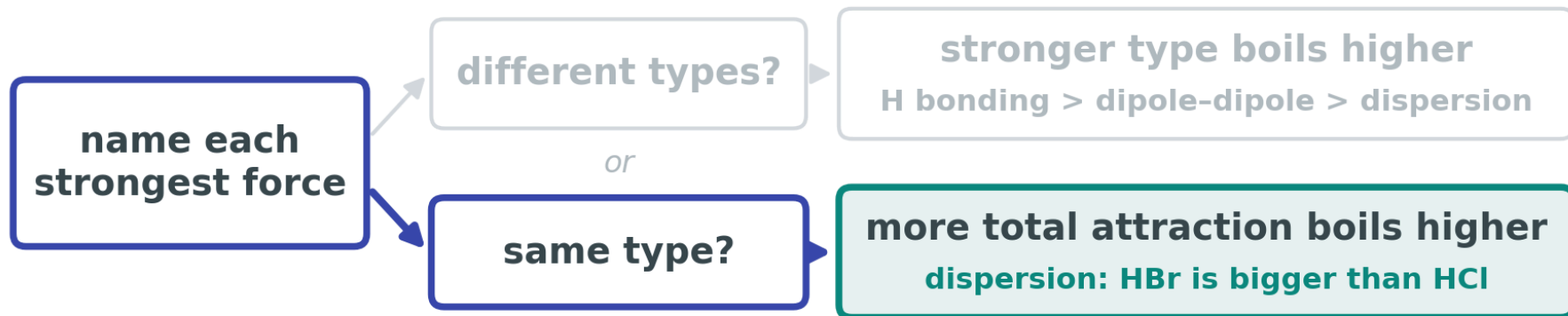
- A. HCl: its larger dipole gives stronger dipole-dipole attraction
- B. HBr: the H on Br adds hydrogen bonding
- C. HBr: the larger molecule has stronger dispersion
- D. HCl: the H on Cl adds hydrogen bonding

✓ Practice 3 answer: C

HCl and HBr: both dipole-dipole, a tie in type · answer C
the bigger molecule breaks the tie · HBr 80.91 vs HCl 36.46 g/mol · HBr $-67\text{ }^{\circ}\text{C}$ vs HCl $-85\text{ }^{\circ}\text{C}$

🧠 **Sense check:** HBr boils $18\text{ }^{\circ}\text{C}$ above HCl, though HCl is the more polar molecule. ✓

The route on the map





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

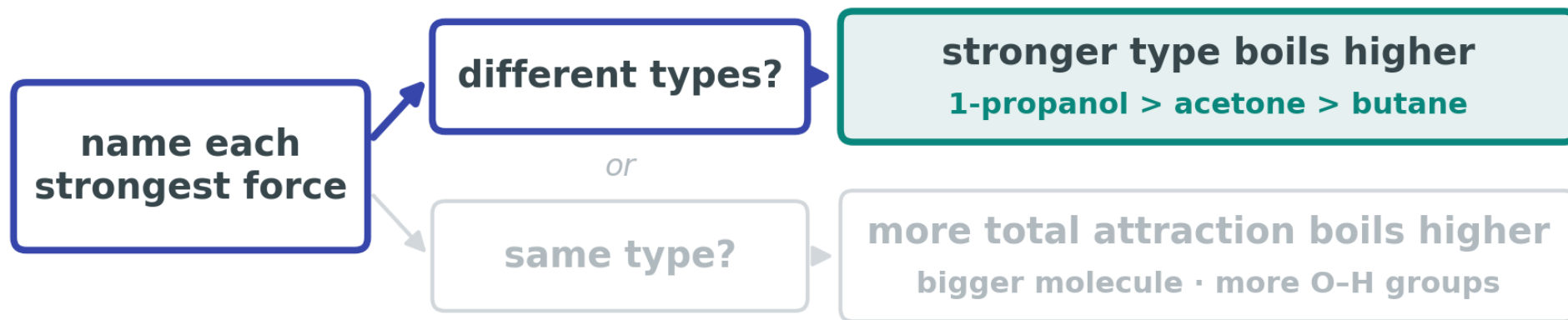
butane $-0.5\text{ }^\circ\text{C}$ · acetone $56\text{ }^\circ\text{C}$ · 1-propanol $97\text{ }^\circ\text{C}$
 dispersion < dipole-dipole < hydrogen bonding · masses within 2 g/mol

 **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 4

neon (Ne) · krypton (Kr) · phosphine (PH₃) · ammonia (NH₃)
20.18 · 83.80 · 34.00 · 17.03 g/mol · PH₃ and NH₃ are polar molecules

Rank the four substances from lowest to highest boiling point.

- A. NH₃ < Ne < PH₃ < Kr
- B. Ne < Kr < NH₃ < PH₃
- C. Kr < Ne < PH₃ < NH₃
- D. Ne < Kr < PH₃ < NH₃

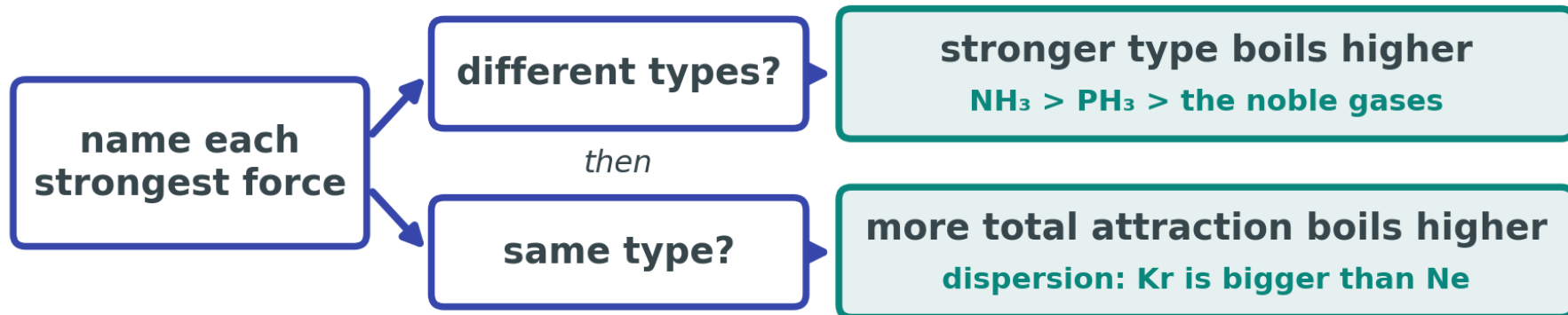
✓ Practice 4 answer: D

Ne < Kr < PH₃ < NH₃ · answer D

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

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

The route on the map



More O-H groups, more hydrogen bonds

1-propanol ($\text{CH}_3\text{CH}_2\text{CH}_2\text{OH}$) 97 °C · ethylene glycol ($\text{HOCH}_2\text{CH}_2\text{OH}$) 197 °C
60.09 vs 62.07 g/mol · one O-H vs two · both hydrogen bond

Both hydrogen bond, at nearly the same mass. Each O-H group is one more site for hydrogen bonds, so two O-H groups hold far tighter. Ethylene glycol boils 100 °C higher.



Practice 5

$\text{CS}_2 \cdot \text{butanone (CH}_3\text{COCH}_2\text{CH}_3) \cdot \text{1-butanol (CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{OH)} \cdot \text{propylene glycol (CH}_3\text{CH(OH)CH}_2\text{OH)}$
 $76.13 \cdot 72.10 \cdot 74.12 \cdot 76.09 \text{ g/mol}$

Rank the four from lowest to highest boiling point.

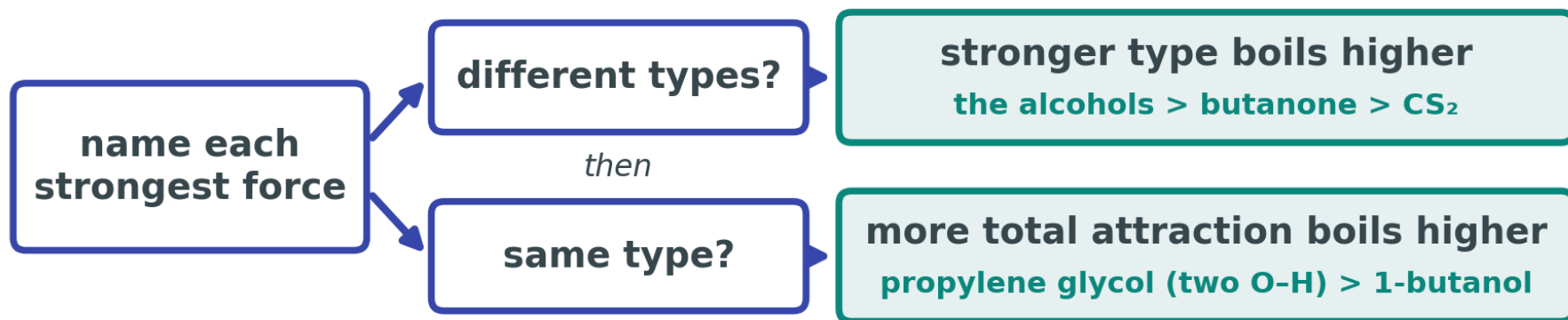
- A. butanone < 1-butanol < propylene glycol < CS_2
- B. CS_2 < butanone < propylene glycol < 1-butanol
- C. propylene glycol < 1-butanol < butanone < CS_2
- D. butanone < CS_2 < 1-butanol < propylene glycol
- E. CS_2 < butanone < 1-butanol < propylene glycol

✓ Practice 5 answer: E

$\text{CS}_2 < \text{butanone} < 1\text{-butanol} < \text{propylene glycol}$ · answer E
dispersion · dipole-dipole · hydrogen bonding, one O-H · hydrogen bonding, two O-H

🧠 **Sense check:** Measured: CS_2 46 °C, butanone 80 °C, 1-butanol 118 °C, propylene glycol 188 °C. Type first, then count the O-H groups. ✓

The route on the map





Practice 6

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 6 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 7

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 7 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 8



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 8 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

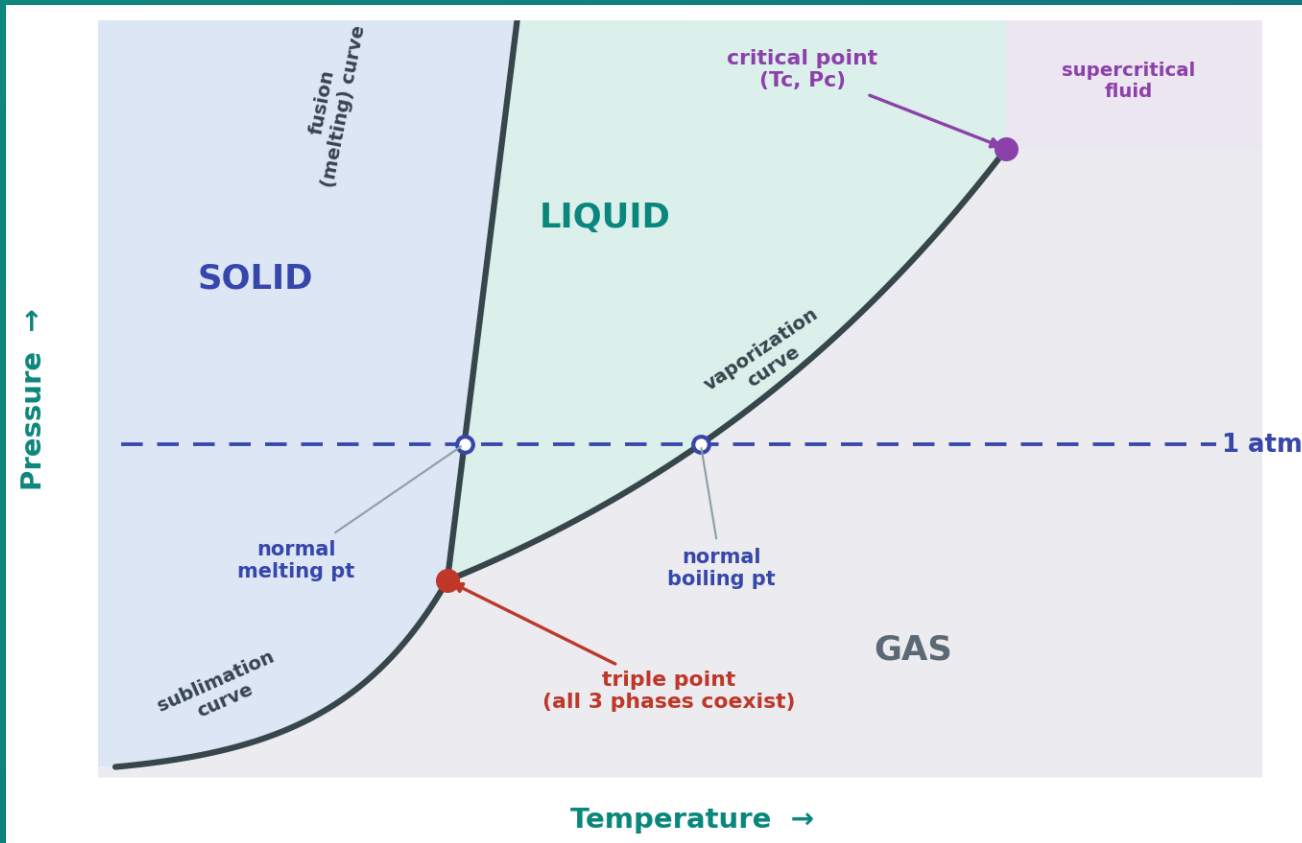
1. Neon and argon are both nonpolar. Which boils at the higher temperature, and which force decides it?
2. Dimethyl ether and ethanol have the same molar mass. Which boils higher, and why?

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

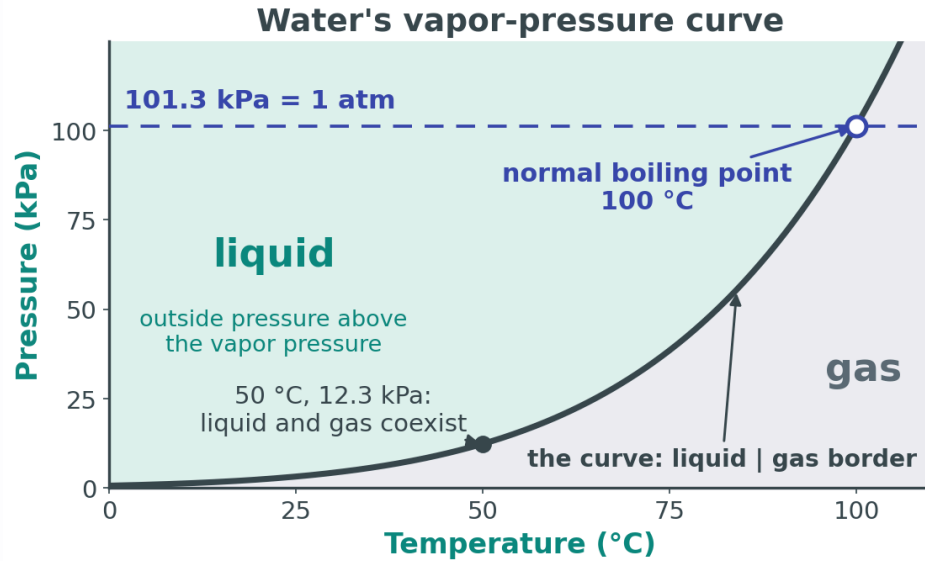
Read a pressure-temperature phase diagram: name the stable phase at any P, T , follow a constant-pressure or constant-temperature path and list the phase changes, and locate the triple point, critical point, and the normal melting and boiling points on the 1-atm line.

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.

The vapor-pressure curve is a border



a liquid boils when its vapor pressure = the outside pressure
water: vapor pressure 101.3 kPa = 1 atm at 100 °C → the normal boiling point

Every point on the curve is a temperature and pressure where liquid and gas coexist. Above it, water stays liquid; below it, gas. A phase diagram draws this border and two more.

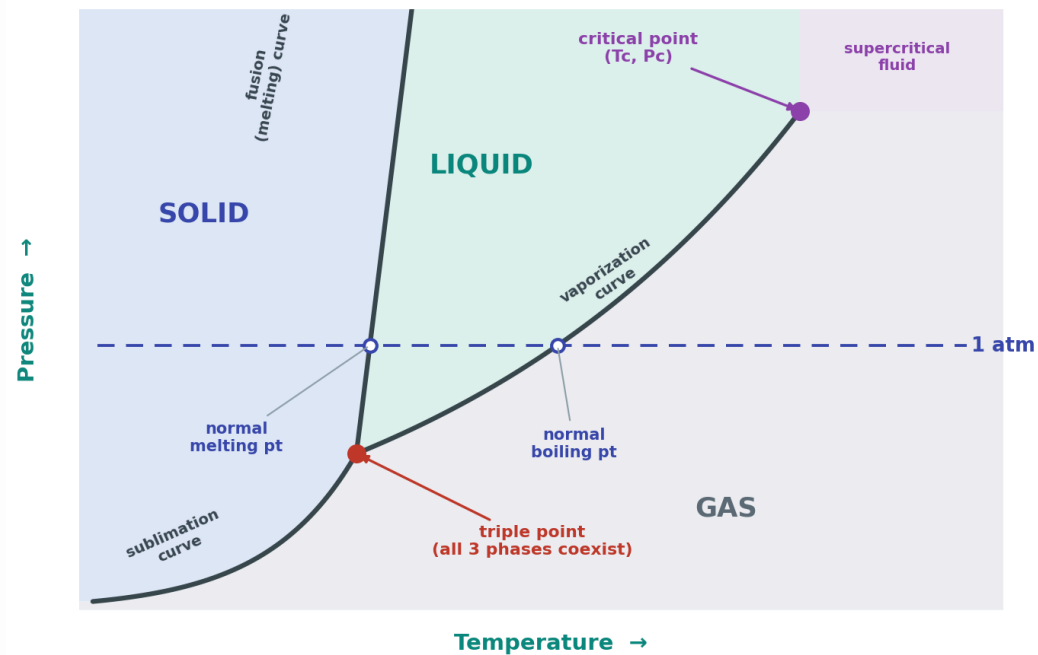
A phase diagram maps pressure vs temperature

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

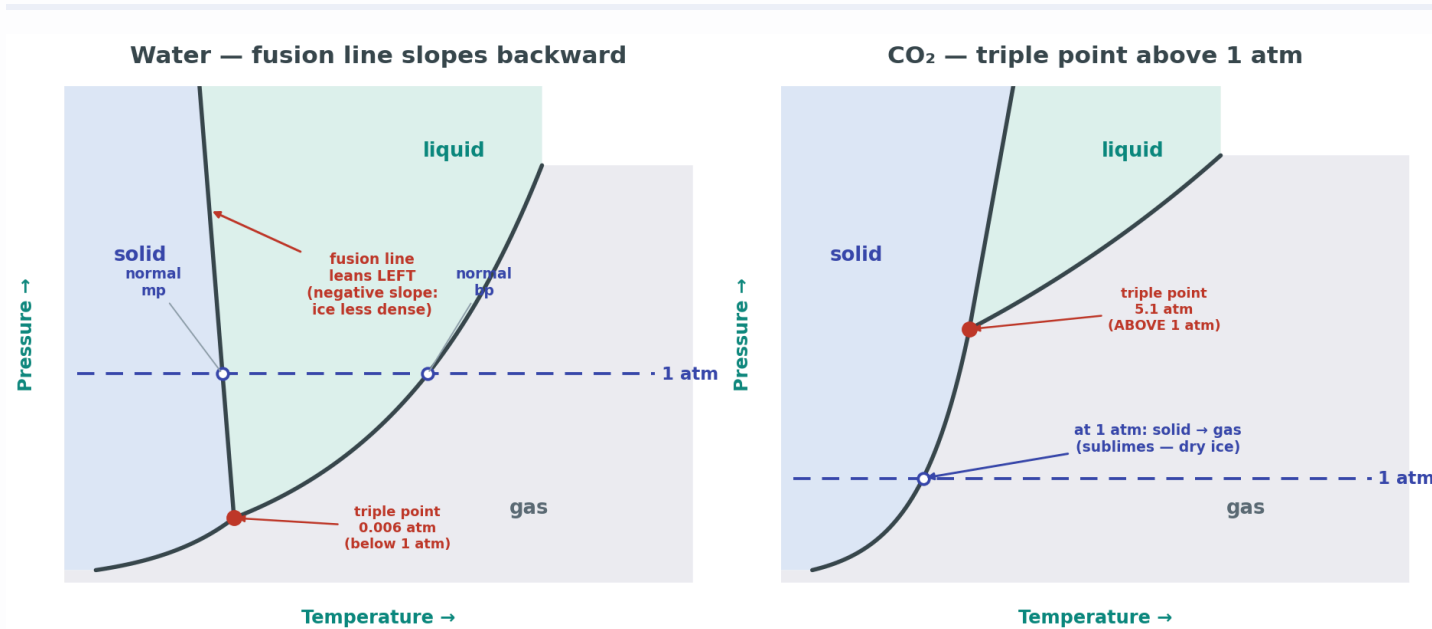
triple point sits low and left · critical point sits at the top of the vaporization curve

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.

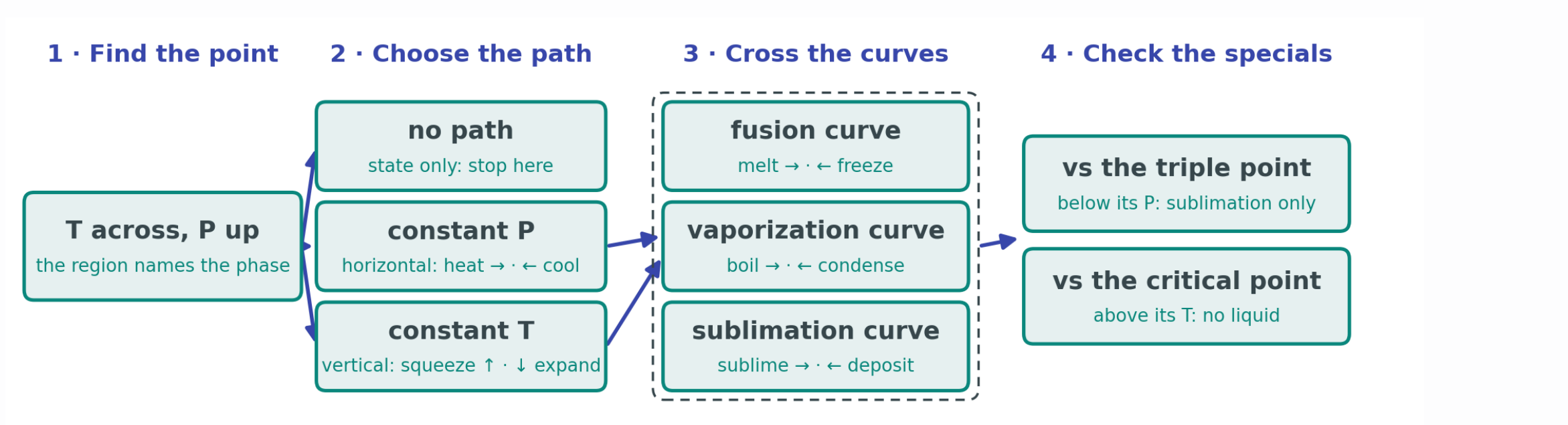
CO₂: triple point at 5.1 atm, above 1 atm
the 1-atm line never reaches the fusion curve · dry ice sublimates instead of melting



Reading a phase diagram

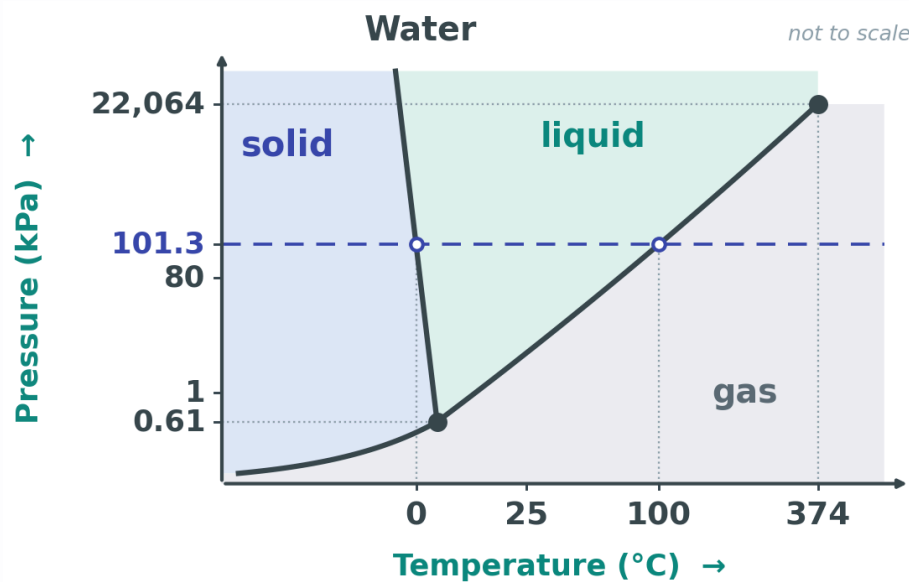
1. **Find the point.** T across, P up; its region names the phase.
2. **Choose the path.** Constant P: horizontal. Constant T: vertical.
3. **Cross the curves.** Each crossing is one phase change.
4. **Check the specials.** Triple point, critical point.

The route through a phase diagram



A state question stops after step 1. A path question lists every curve it crosses, in order, then checks that list against the triple point and the critical point.

✎ Guided example: water at 25 °C

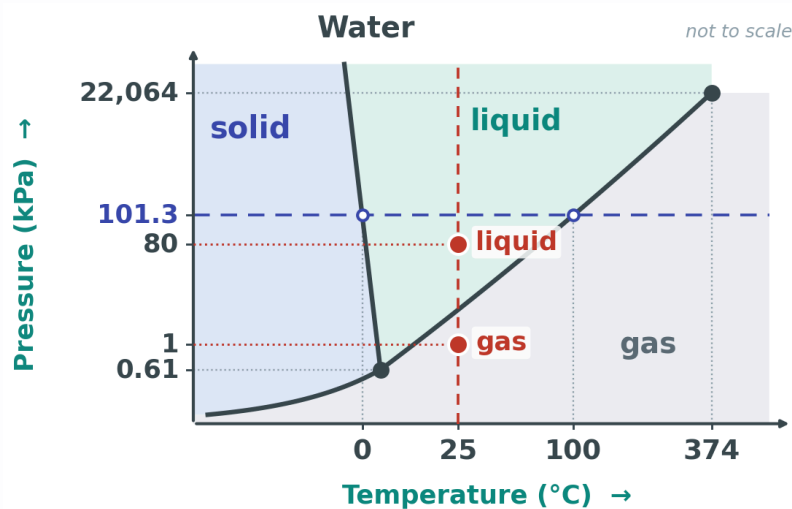


water at 25 °C: once at 80 kPa, once at 1 kPa

given: water's phase diagram in kPa · wanted: the state at each point

Find the state of water at each point. Three moves per point: temperature across, pressure up, read the region.

✓ Guided example: solution



Step 1 · Find the point

25 °C, 80 kPa → liquid · 25 °C, 1 kPa → gas

one temperature, two pressures · the vaporization curve lies between them

🧠 **Sense check:** Water's vapor pressure at 25 °C is 3.17 kPa. At 80 kPa the outside pressure is higher: liquid. At 1 kPa it is lower: gas. ✓

✓ Guided example: the route on the map

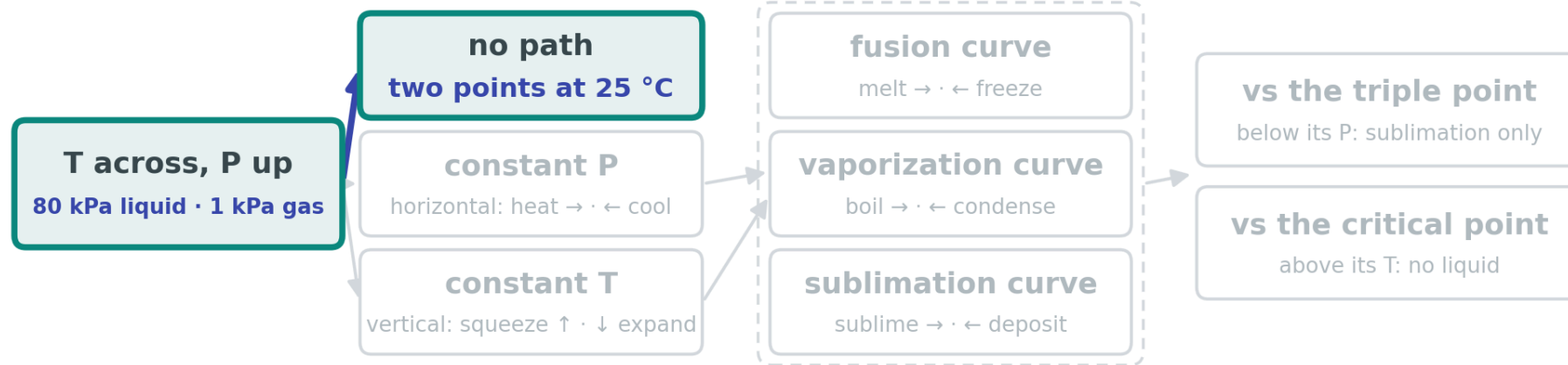
25 °C, 80 kPa → liquid · 25 °C, 1 kPa → gas
given: two points on water's diagram · found: the state at each

1 · Find the point

2 · Choose the path

3 · Cross the curves

4 · Check the specials



🧠 **Sense check:** A state question: step 1 only. With no path, no curve is crossed. ✓



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

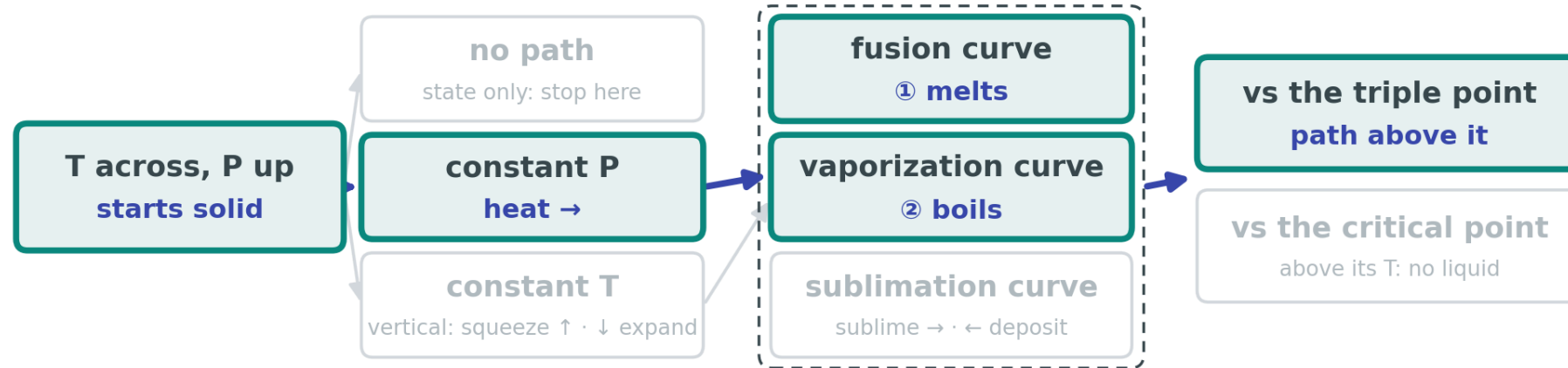
solid → (cross fusion) → liquid → (cross vaporization) → gas
 heat at constant pressure · the path runs above the triple-point pressure

1 · Find the point

2 · Choose the path

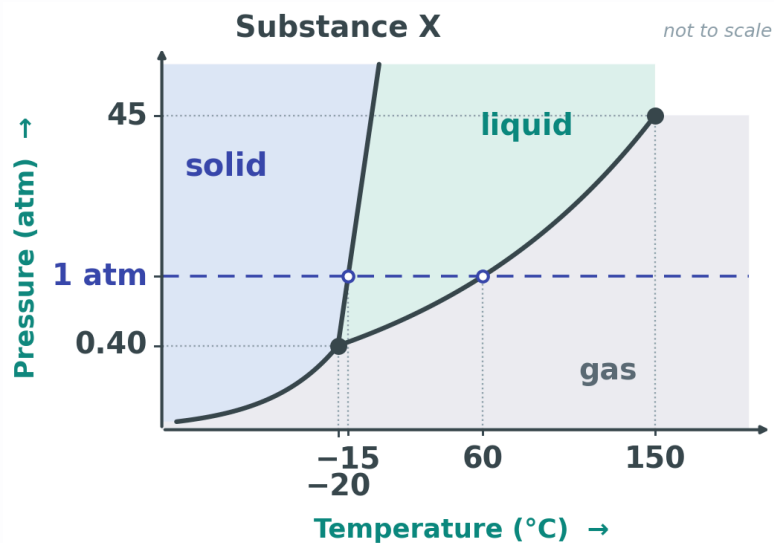
3 · Cross the curves

4 · Check the specials



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

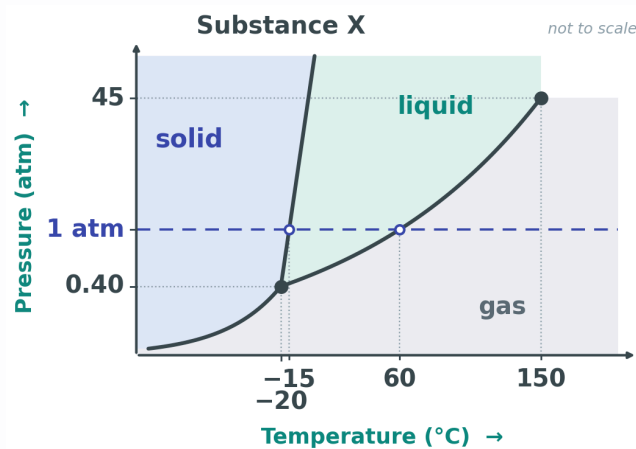
Worked example 2: reading substance X



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

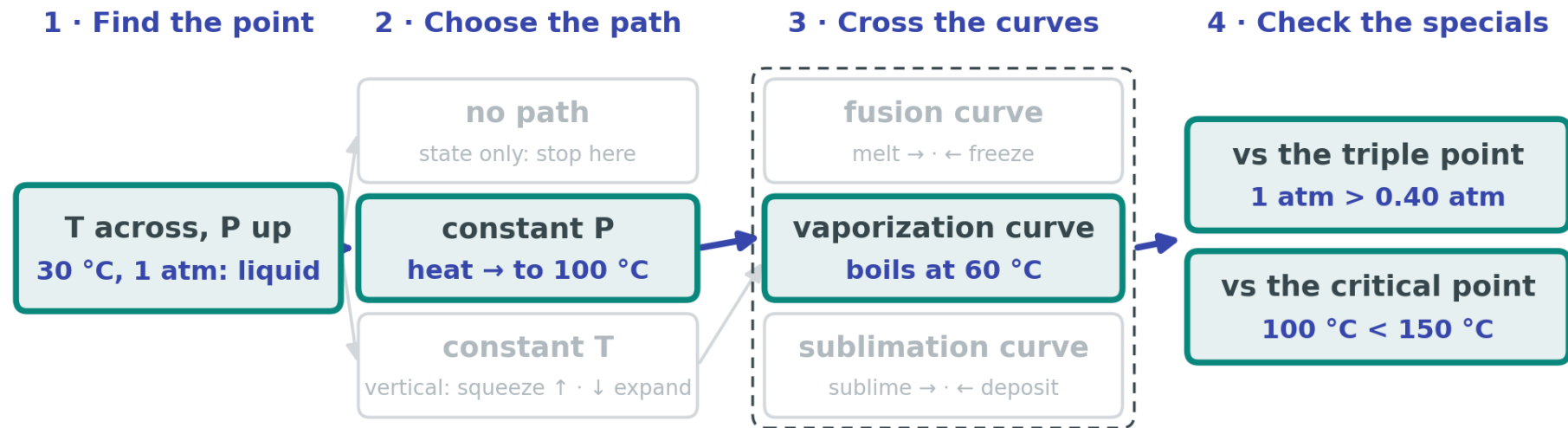
Step 3 · Cross the curves

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. ✓

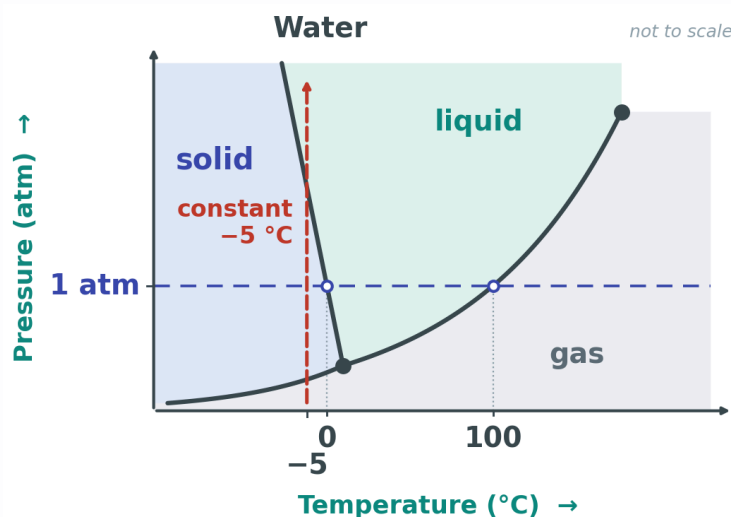
✓ Worked example 2: the route on the map

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



🧠 **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: ——— $\rightarrow$ becomes ——— · second curve: ——— $\rightarrow$ becomes ———

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

✓ Your turn: the route on the map

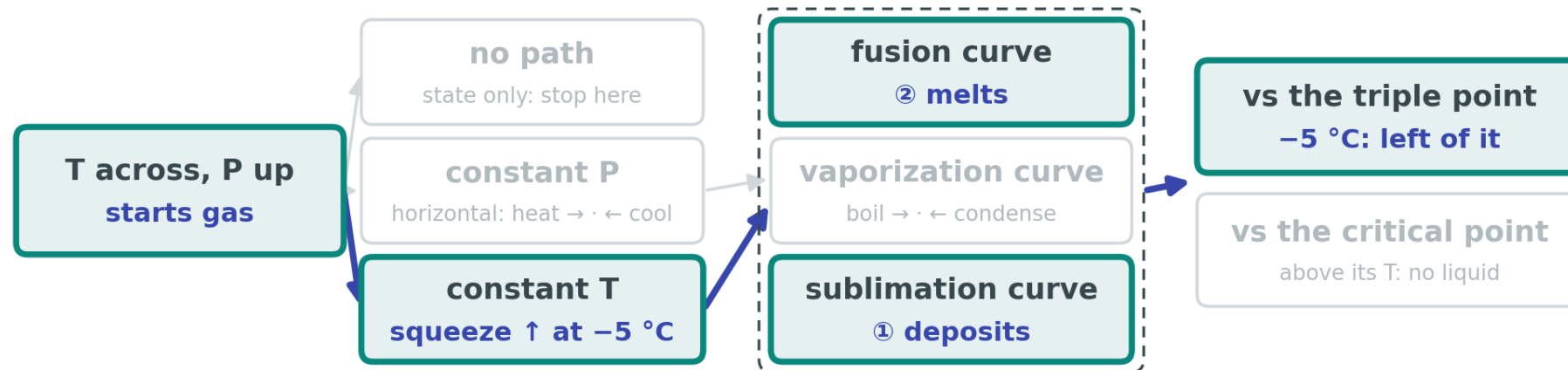
gas → (sublimation curve) → solid → (fusion curve) → liquid
 water · constant $-5\text{ }^{\circ}\text{C}$ · squeezed up from low pressure

1 · Find the point

2 · Choose the path

3 · Cross the curves

4 · Check the specials



🧠 **Sense check:** A vertical path holds the temperature. At $-5\text{ }^{\circ}\text{C}$ it starts left of the triple point, so the sublimation curve comes first. ✓

⚠ Where this goes wrong

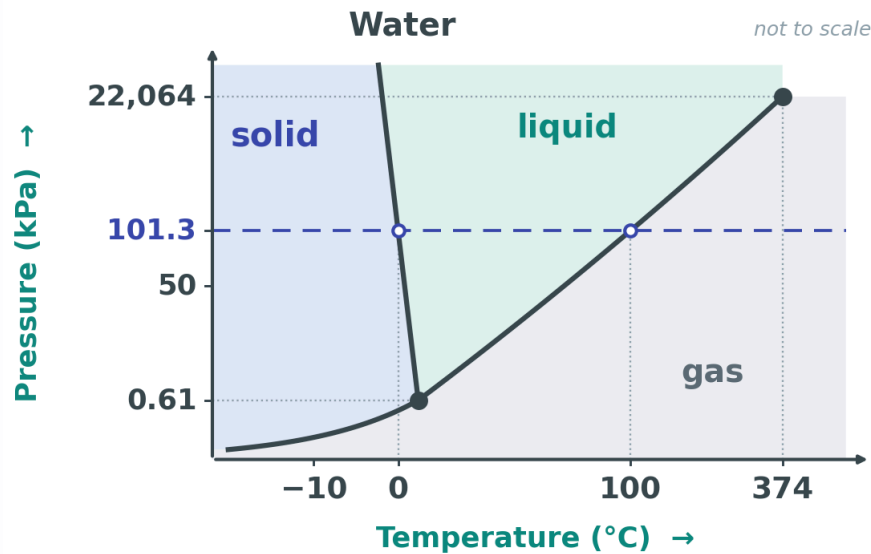
Swapping the axes. Temperature is the horizontal axis, pressure the vertical: read T across the bottom, P up the side, not the reverse.

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.

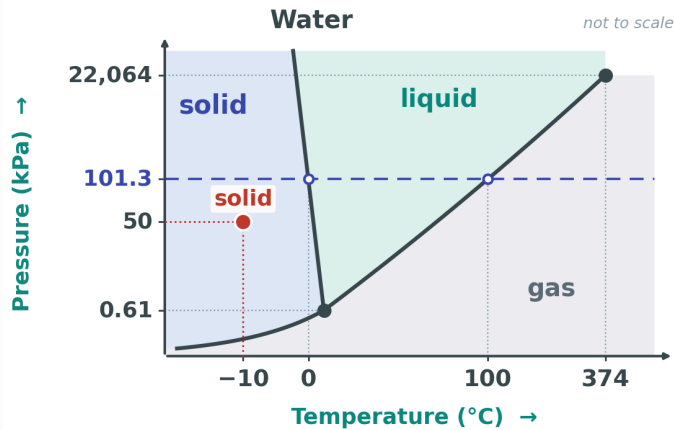
Practice 1



What is the state of water at -10°C and 50 kPa?

- A. liquid
- B. solid
- C. gas

✓ Practice 1 answer: B



**–10 °C across, 50 kPa up → left of the fusion curve, above the sublimation curve
the solid region · answer B**

A took the left-leaning fusion curve to mean cold water under pressure is liquid; at –10 °C that needs about 110,000 kPa (1,100 atm), and 50 kPa is half an atmosphere. C read any pressure below 101.3 kPa as gas; at –10 °C the gas region lies below 0.26 kPa.

 **Sense check:** Below 0 °C, and far above the 0.61-kPa triple point: ice. ✓

✓ Practice 1: the route on the map

–10 °C, 50 kPa → solid

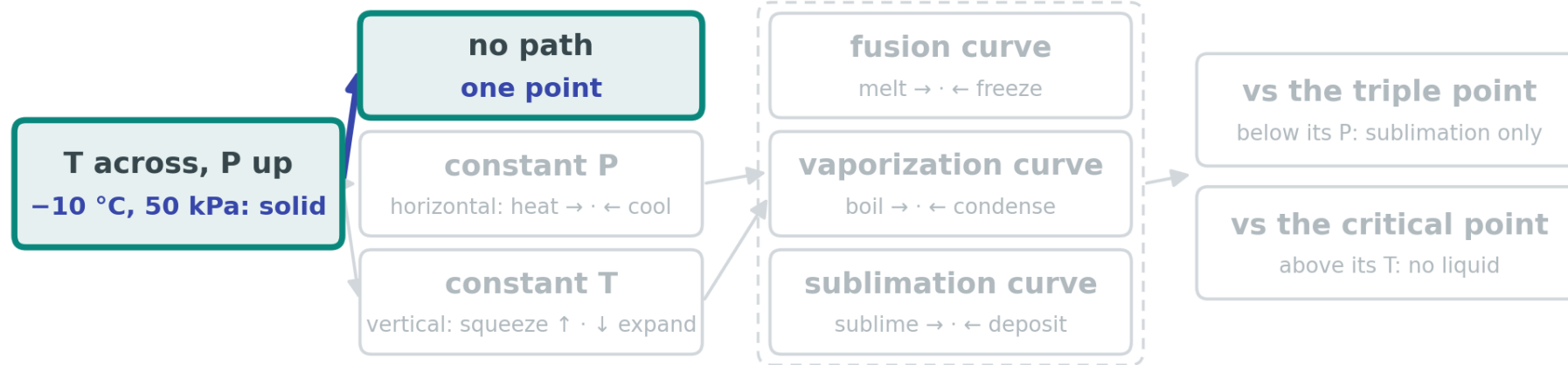
given: one point on water's diagram · found: its state

1 · Find the point

2 · Choose the path

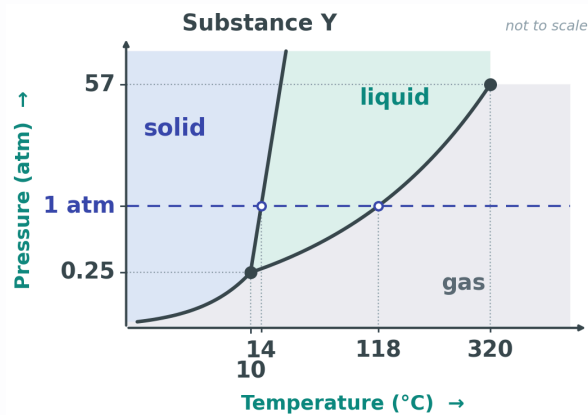
3 · Cross the curves

4 · Check the specials



🧠 **Sense check:** The same single step as the guided example: find the point, read the region. ✓

Practice 2



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 2 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: the route on the map

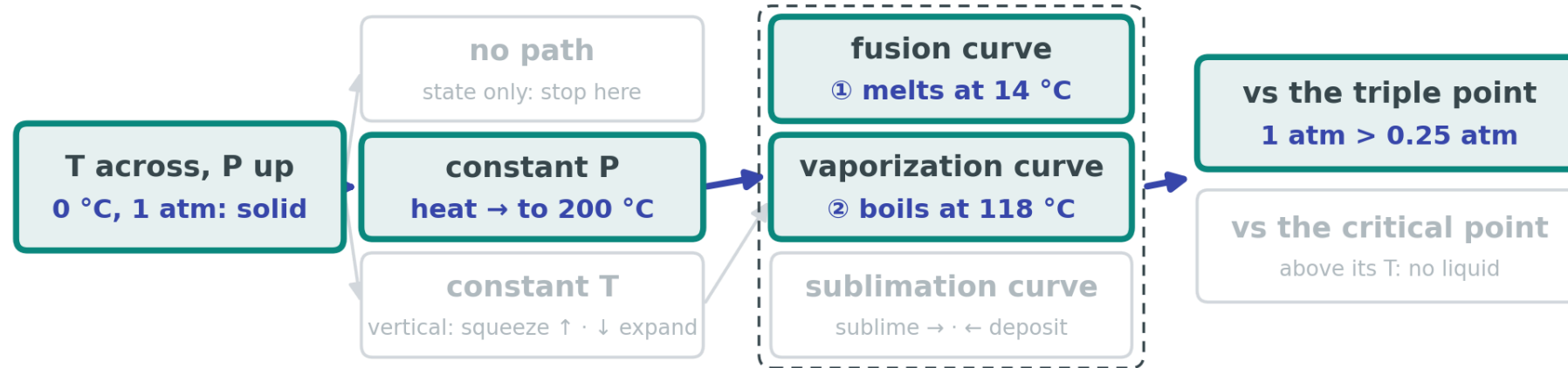
1-atm line: melts at 14 °C, then boils at 118 °C
 substance Y · heated at 1 atm, above the 0.25-atm triple point

1 · Find the point

2 · Choose the path

3 · Cross the curves

4 · Check the specials



🧠 **Sense check:** The same two crossings as worked example 1, now with temperatures read off the axis. ✓

Practice 3: freeze-drying

water: triple point $0.01\text{ }^{\circ}\text{C}$, 0.61 kPa · normal melting point $0\text{ }^{\circ}\text{C}$ · normal boiling point $100\text{ }^{\circ}\text{C}$

frozen strawberries at $-30\text{ }^{\circ}\text{C}$ · held at 0.10 kPa · warmed at constant pressure to $20\text{ }^{\circ}\text{C}$

A freeze-dryer pumps the pressure down, then warms the frozen fruit. What happens to the ice?

- A. It sublimates: solid straight to gas
- B. It melts at $0\text{ }^{\circ}\text{C}$ and is still liquid at $20\text{ }^{\circ}\text{C}$
- C. It melts, then the water boils away
- D. It undergoes deposition

✓ Practice 3 answer: A

0.10 kPa lies below the 0.61-kPa triple point → the path meets only the sublimation curve · answer A

$0.61 - 0.10 = 0.51$ kPa below the triple point · the ice turns to vapor near $-20\text{ }^{\circ}\text{C}$

B used the 1-atm points: $0\text{ }^{\circ}\text{C}$ and $100\text{ }^{\circ}\text{C}$ hold only at 101.3 kPa. C sent the path through the liquid region, which exists only above 0.61 kPa. D named the change backward: deposition runs gas → solid.

🧠 **Sense check:** No liquid ever forms, so the fruit dries without turning soggy. That is the point of freeze-drying. ✓

✓ Practice 3: the route on the map

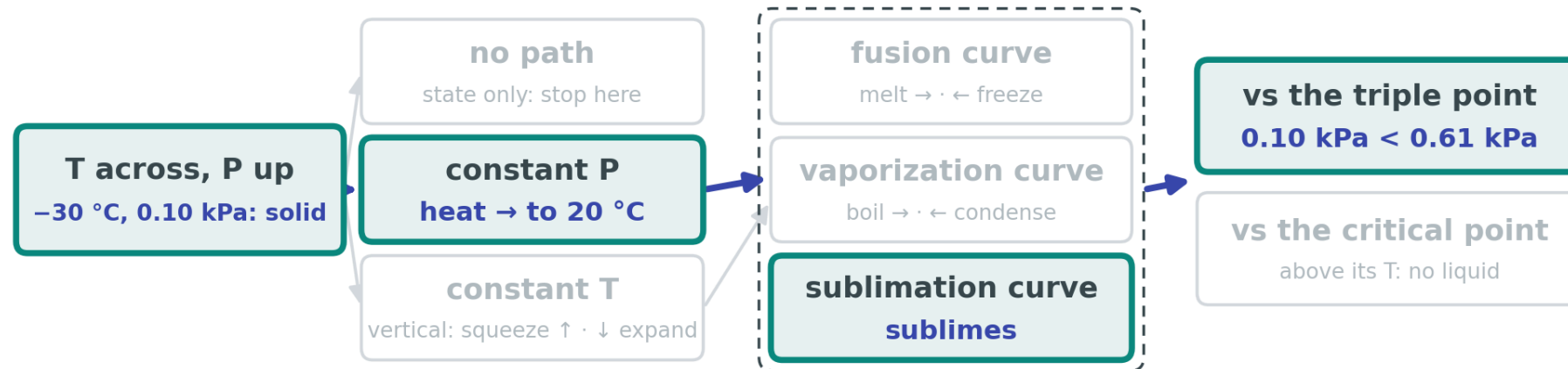
ice at 0.10 kPa → (sublimation curve) → vapor
water · heated at constant pressure · 0.10 kPa < 0.61 kPa

1 · Find the point

2 · Choose the path

3 · Cross the curves

4 · Check the specials



🧠 **Sense check:** Below the triple-point pressure, a heating path meets one curve only. ✓



Practice 4

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 4 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 4: the route on the map

20 atm: condenses, then freezes

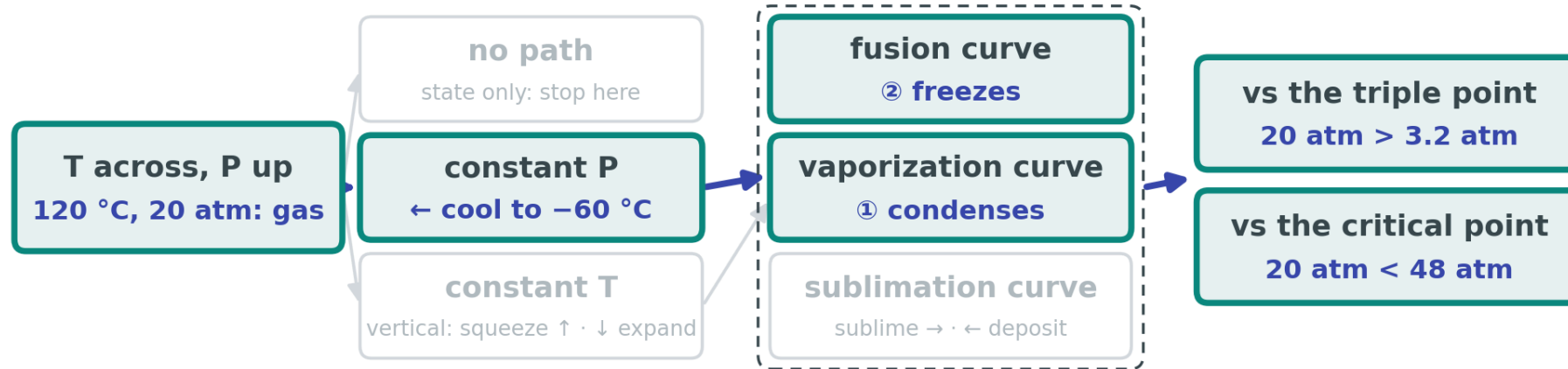
substance W · $3.2 \text{ atm} < 20 \text{ atm} < 48 \text{ atm}$ · cooled from 120°C to -60°C

1 · Find the point

2 · Choose the path

3 · Cross the curves

4 · Check the specials



🧠 **Sense check:** Cooling runs the path right to left, so each curve is crossed in reverse: condense, then freeze. ✓



Practice 5

substance Q: triple point $-35\text{ }^{\circ}\text{C}$, 0.80 atm · critical point $120\text{ }^{\circ}\text{C}$, 38 atm
fusion curve slopes up to the right · start: gas at $60\text{ }^{\circ}\text{C}$, 0.20 atm · squeezed at $60\text{ }^{\circ}\text{C}$ up to 50 atm

What does the sample go through as the pressure rises?

- A. Deposition only (gas $\rightarrow$ solid)
- B. Condensation (gas $\rightarrow$ liquid), then freezing (liquid $\rightarrow$ solid)
- C. No change: past 38 atm it is a supercritical fluid
- D. Condensation only (gas $\rightarrow$ liquid)

✓ Practice 5 answer: D

$60\text{ }^{\circ}\text{C} - (-35\text{ }^{\circ}\text{C}) = 95\text{ }^{\circ}\text{C}$ above the triple point ·

$120\text{ }^{\circ}\text{C} - 60\text{ }^{\circ}\text{C} = 60\text{ }^{\circ}\text{C}$ below the critical point → **condensation only, answer D**

The vertical path at $60\text{ }^{\circ}\text{C}$ crosses the vaporization curve once. The steep fusion curve rises from $-35\text{ }^{\circ}\text{C}$ and never reaches $60\text{ }^{\circ}\text{C}$.

A compared the starting 0.20 atm with the 0.80-atm triple point; a vertical path is judged by its temperature. B went on across the fusion curve, as a cooling path would. C checked only the pressure: 50 atm is 12 atm past 38 atm , but a supercritical fluid also needs a temperature above $120\text{ }^{\circ}\text{C}$.

🧠 **Sense check:** Between the triple-point and critical temperatures, squeezing a gas makes a liquid, and more pressure keeps it liquid. ✓

✓ Practice 5: the route on the map

0.20 atm → 50 atm at 60 °C: condenses
 substance Q · $-35\text{ °C} < 60\text{ °C} < 120\text{ °C}$

1 · Find the point

T across, P up
 60 °C, 0.20 atm: gas

2 · Choose the path

no path
 state only: stop here

constant P
 horizontal: heat → · ← cool

constant T
 squeeze ↑ to 50 atm

3 · Cross the curves

fusion curve
 melt → · ← freeze

vaporization curve
 condenses

sublimation curve
 sublime → · ← deposit

4 · Check the specials

vs the triple point
 60 °C > -35 °C

vs the critical point
 60 °C < 120 °C

🧠 **Sense check:** A vertical path is checked by its temperature. Between the triple point and the critical point, it crosses one curve. ✓



Practice 6

water's vapor pressure at 60 °C: 19.9 kPa

normal boiling point 100 °C · a sealed sample of water held at 60 °C and 19.9 kPa

Which statement best describes the water?

- A. All gas: the pressure is below 101.3 kPa
- 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 6 answer: D

outside pressure = vapor pressure → on the vaporization curve · answer D
60 °C, 19.9 kPa · 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 101.3 kPa as gas; at 60 °C the gas region starts only below 19.9 kPa. B used the normal boiling point at every pressure; 60 °C is 40 °C below it, but at 19.9 kPa 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 19.9 kPa: liquid. Below it: gas. Exactly at it: both, the same balance as the vapor over a liquid in a sealed flask. ✓



Practice 7

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 7 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

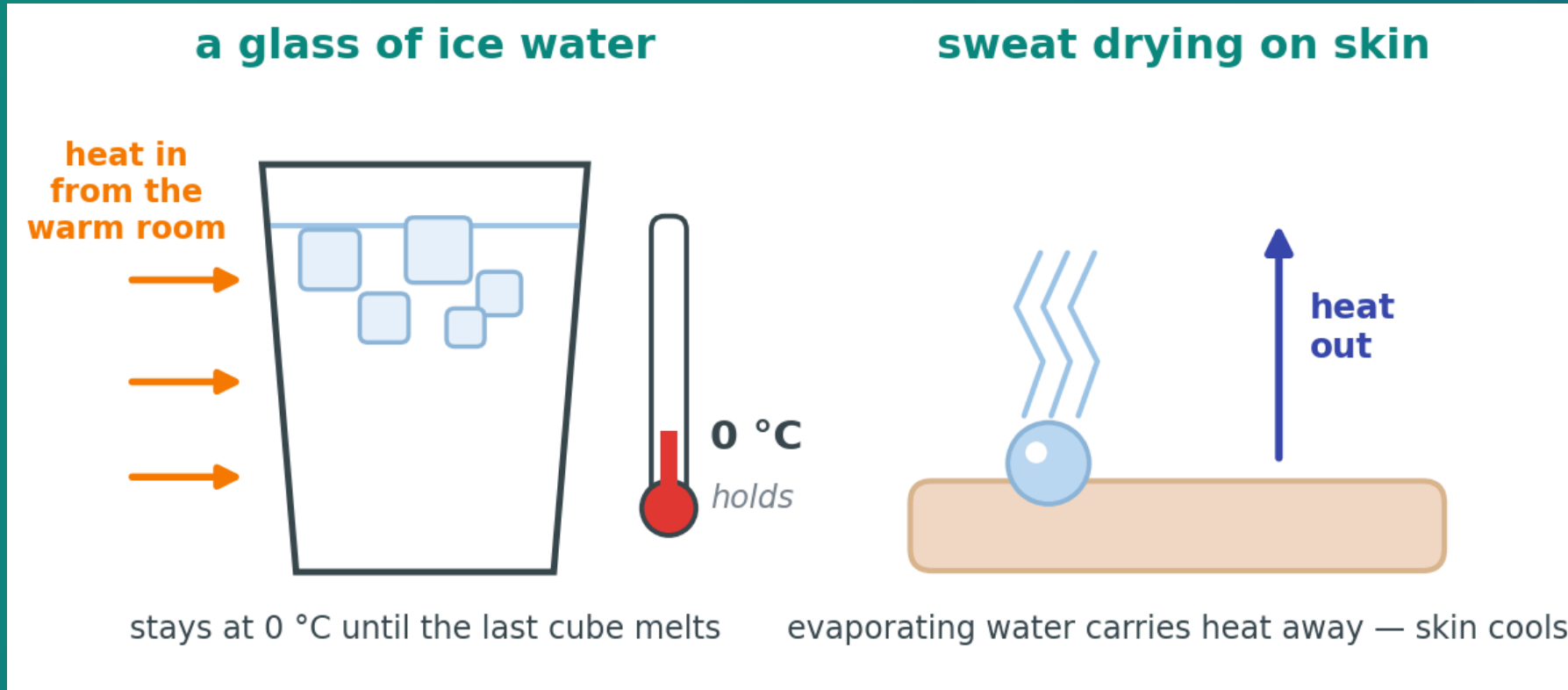
1. A substance with a normal fusion curve is heated at a constant pressure above its triple point. Which curve does the path cross first, and what phase change is it?
2. Why can raising the pressure on ice just below 0 °C melt it, when raising the pressure on most solids does the opposite?

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 • Heat of a Phase Change

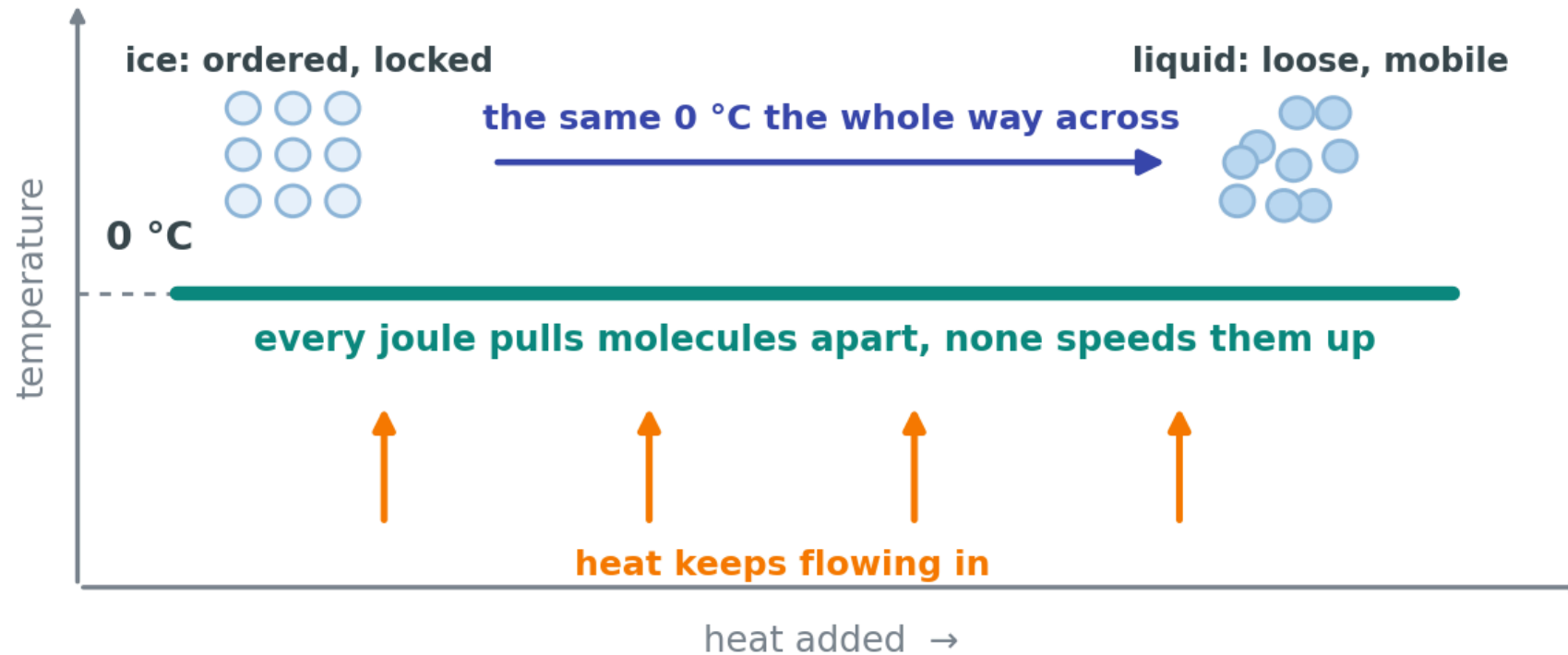
Find the heat of a phase change with $q = \text{mass} \times \Delta H$ in J/g or $q = n \times \Delta H$ in kJ/mol, choosing the heat of fusion for melting or freezing and the heat of vaporization for boiling or condensing, while the temperature holds constant.

Heat flows, the temperature holds



A glass of ice water stays at 0 °C until the last cube melts. Sweat cools your skin. Heat moves in or out; the temperature holds.

Temperature holds during a phase change



A phase change runs at one temperature. The heat does not warm the sample; it pulls the molecules apart. Ice water holds at 0 °C until the last cube melts.

A fixed heat for every mole

melting ice at 0 °C takes 6.02 kJ per mole

twice the moles, twice the heat · the temperature stays at 0 °C the whole time

Each mole of ice takes the same heat to melt. As a conversion factor, that heat cancels moles:

$$2.00 \text{ mol} \times \frac{6.02 \text{ kJ}}{1 \text{ mol}} = 12.0 \text{ kJ}$$

How much heat melts 0.500 mol of ice?

$$0.500 \text{ mol} \times \frac{6.02 \text{ kJ}}{1 \text{ mol}} = 3.01 \text{ kJ}$$

Half a mole takes half the heat.

Six changes of state

absorbs heat · endothermic



releases heat · exothermic



Changes toward the gas pull particles apart and absorb heat: endothermic. The reverses release that same heat: exothermic. Vaporization is also called evaporation. Dry ice goes straight from solid to gas; so does iodine warmed gently.

Heat of fusion and heat of vaporization

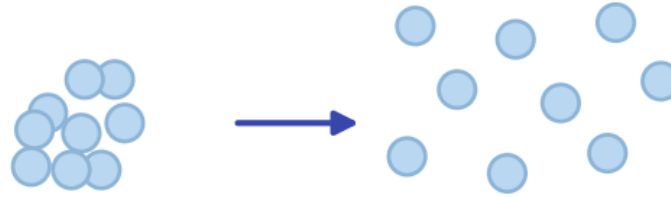
**for water: $\Delta H_{\text{fus}} = 335 \text{ J/g}$ · $\Delta H_{\text{vap}} = 2259 \text{ J/g}$
melt or freeze: 335 J per gram · boil or condense: 2259 J per gram**

Melting is called fusion. The heat of fusion, ΔH_{fus} , melts one gram; the heat of vaporization, ΔH_{vap} , boils one gram. Freezing and condensing release the same amounts, reversed.

Vaporizing costs more than melting



melting: loosen the packing
(molecules still touch)



vaporizing: pull fully apart
(molecules fly free)

melt  **heat of fusion 335 J/g**

vaporize  **heat of vaporization 2259 J/g**

water: vaporizing takes about 7 times the heat of melting

ΔH_{vap} is far larger than ΔH_{fus} . Melting only loosens the packing; the molecules still touch. Vaporizing pulls them fully apart, which takes about seven times the energy.

The phase-change heat equation

$$q = \text{mass} \times \Delta H$$

$$\text{g} \times (\text{J/g}) = \text{J} \cdot \text{absorbed (+) to melt or boil} \cdot \text{released (-) to freeze or condense}$$

Each heat is a conversion factor in joules per gram. Multiply by the mass and grams cancel. Melting and boiling absorb heat; freezing and condensing release it, so q turns negative.

The same heats, per mole

$$q = n \times \Delta H$$

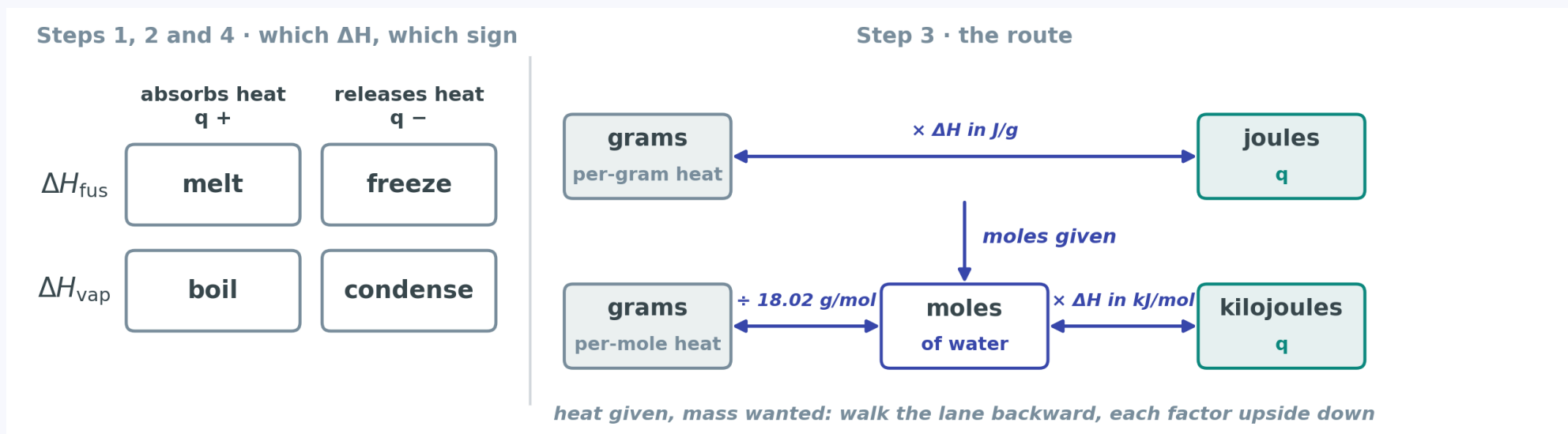
for water: $\Delta H_{\text{fus}} = 6.02 \text{ kJ/mol}$ · $\Delta H_{\text{vap}} = 40.7 \text{ kJ/mol}$ · grams → moles → kilojoules

Phase-change heats also come per mole: 6.02 kJ melts a mole of ice, 40.7 kJ boils a mole of water. A mass in grams becomes moles first; either route lands on the same heat.



The method

1. **Name the phase change.**
2. **Pick its ΔH :** fusion to melt or freeze, vaporization to boil or condense.
3. **Multiply:** mass $\times \Delta H$ (J/g), or moles $\times \Delta H$ (kJ/mol).
4. **Set the direction:** melting and boiling absorb; freezing and condensing release.





Guided example: boiling off a pot of water

$$q = n \times \Delta H$$

given: 2.50 mol water boils at 100 °C · $\Delta H_{\text{fus}} = 6.02 \text{ kJ/mol}$ · $\Delta H_{\text{vap}} = 40.7 \text{ kJ/mol}$ · wanted: q in kJ

A pot of water at 100 °C boils until **2.50 mol** of it has turned to steam. How much heat did the water absorb, in kJ?

Two molar heats are listed. Name the change first; the change picks the heat.

✓ Guided example: solution

$$q = n \times \Delta H$$

given: 2.50 mol water boils at 100 °C · $\Delta H_{\text{fus}} = 6.02 \text{ kJ/mol}$ · $\Delta H_{\text{vap}} = 40.7 \text{ kJ/mol}$

Step 1 · Name the phase change

Step 2 · Pick its ΔH

Step 3 · Multiply

$$2.50 \text{ mol} \times \frac{40.7 \text{ kJ}}{1 \text{ mol}} = 102 \text{ kJ}$$

Step 4 · Set the direction

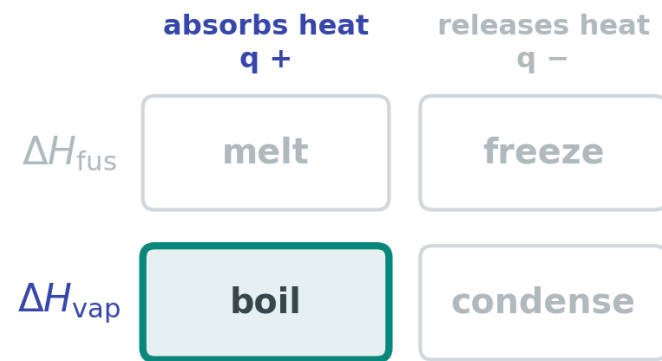
 **Sense check:** Boiling absorbs heat, so q is positive: $q = +102 \text{ kJ}$. Each mole takes about 41 kJ, so 2.50 mol take about 100 kJ. ✓

✓ Guided example: the route on the map

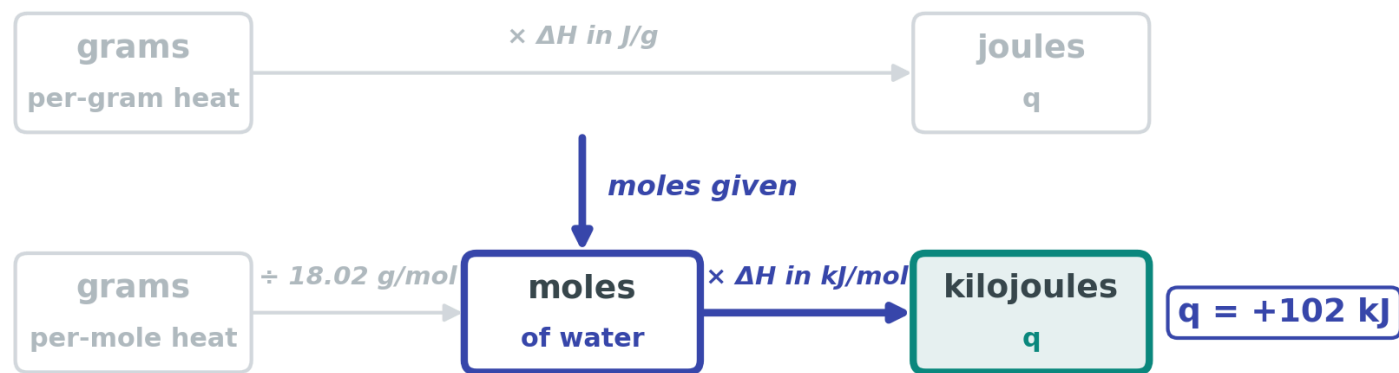
$$q = n \times \Delta H_{\text{vap}}$$

given: 2.50 mol water boils at 100 °C · found: $q = +102 \text{ kJ}$

Steps 1, 2 and 4 · which ΔH , which sign



Step 3 · the route



 **Sense check:** Boiling picks ΔH_{vap} and a plus sign. Moles were given, so the route starts at the moles box: one factor to kilojoules. ✓

 Practice 1

$$q = n \times \Delta H$$

given: 1.60 mol steam condenses at 100 °C · $\Delta H_{\text{fus}} = 6.02 \text{ kJ/mol}$ · $\Delta H_{\text{vap}} = 40.7 \text{ kJ/mol}$

Shower steam at 100 °C hits a cold mirror, and **1.60 mol** of it condenses to liquid water. How much heat, in kJ, does the steam release?

- A. 9.63
- B. 0.0393
- C. 40.7
- D. 65.1

✓ Practice 1 answer: D

$$q = n \times \Delta H_{\text{vap}}$$

condensing is boiling reversed: the vaporization heat applies · 1.60 mol · wanted: heat released

$$1.60 \text{ mol} \times \frac{40.7 \text{ kJ}}{1 \text{ mol}} = 65.1 \text{ kJ} \cdot \text{answer D}$$

A used the heat of fusion: $1.60 \times 6.02 = 9.63$, but nothing melts or freezes. B put the heat per mole upside down: $1.60 \div 40.7 = 0.0393$, and moles do not cancel. C is the heat for one mole alone; the steam is 1.60 mol.

🧠 **Sense check:** Condensing releases what boiling absorbs, 40.7 kJ per mole, so q for the steam is -65.1 kJ . ✓

✓ Practice 1: the route on the map

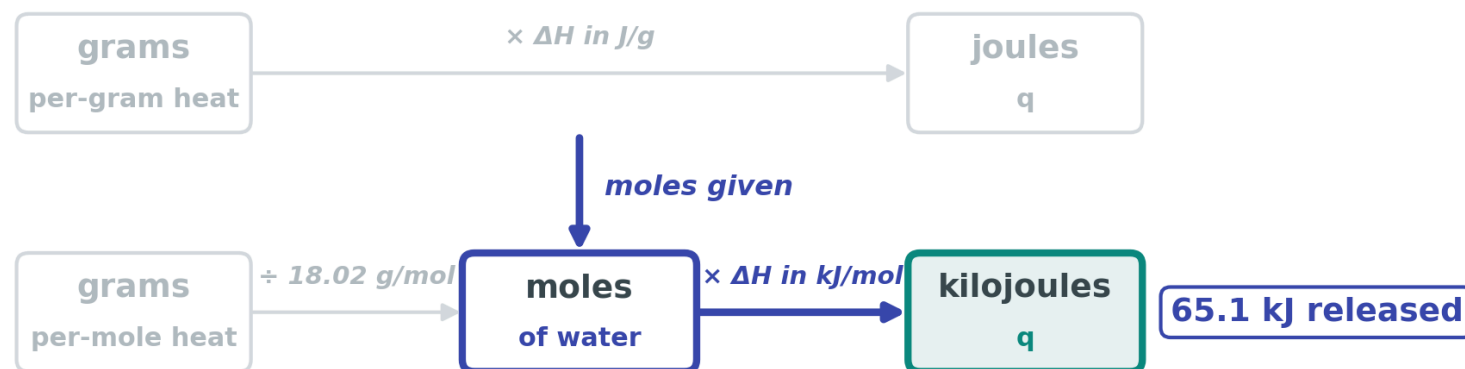
$$q = n \times \Delta H_{\text{vap}}$$

given: 1.60 mol steam condenses at 100 °C · found: 65.1 kJ released

Steps 1, 2 and 4 · which ΔH , which sign

	absorbs heat q +	releases heat q -
ΔH_{fus}	melt	freeze
ΔH_{vap}	boil	condense

Step 3 · the route



🧠 **Sense check:** Condensing sits in the releases column with ΔH_{vap} . Moles were given: one factor to kilojoules. ✓



Worked example 1: melt ice

$$q = \text{mass} \times \Delta H_{\text{fus}}$$

given: 60.0 g ice at 0 °C · $\Delta H_{\text{fus}} = 335 \text{ J/g}$ · wanted: q

A tray holds **60.0 g of ice** at 0 °C. How much heat melts it completely? (ΔH_{fus} of water: 335 J/g)

Name the change of state, then pick its heat.

✓ Worked example 1: solution

$$q = \text{mass} \times \Delta H_{\text{fus}}$$

given: 60.0 g ice at 0 °C · $\Delta H_{\text{fus}} = 335 \text{ J/g}$ · wanted: q

Step 1 · Name the phase change

Step 2 · Pick its ΔH

Step 3 · Multiply

$$60.0 \text{ g} \times \frac{335 \text{ J}}{1 \text{ g}} = 20,100 \text{ J}$$

Step 4 · Set the direction

 **Sense check:** Melting absorbs heat, so q is positive: 20,100 J (20.1 kJ) go in, and the temperature never leaves 0 °C. ✓

✓ Worked example 1: the route on the map

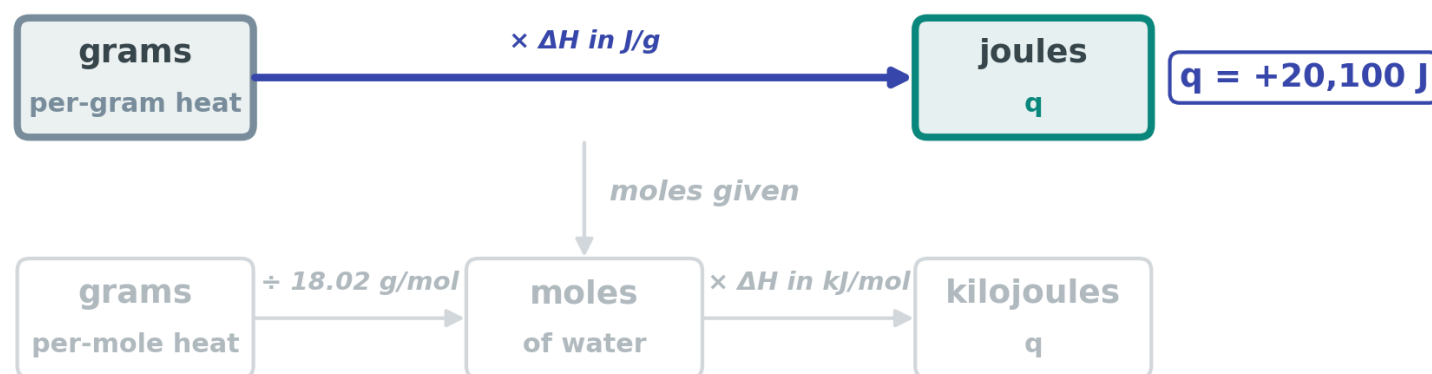
$$q = \text{mass} \times \Delta H_{\text{fus}}$$

given: 60.0 g ice at 0 °C · found: $q = +20,100 \text{ J}$

Steps 1, 2 and 4 · which ΔH , which sign



Step 3 · the route



 **Sense check:** Melting picks ΔH_{fus} and a plus sign. Grams in with a per-gram heat: the top lane, one factor. ✓



Worked example 2: boil water to steam

$$q = \text{mass} \times \Delta H_{\text{vap}}$$

given: 20.0 g water at 100 °C · $\Delta H_{\text{vap}} = 2259 \text{ J/g}$ · wanted: q

20.0 g of water at 100 °C boils away to steam. How much heat does it take? (ΔH_{vap} of water: 2259 J/g)

Same route as melting, with the vaporization heat.

✓ Worked example 2: solution

$$q = \text{mass} \times \Delta H_{\text{vap}}$$

given: 20.0 g water at 100 °C · $\Delta H_{\text{vap}} = 2259 \text{ J/g}$ · wanted: q

Step 1 · Name the phase change

Step 2 · Pick its ΔH

Step 3 · Multiply

$$20.0 \text{ g} \times \frac{2259 \text{ J}}{1 \text{ g}} = 45,180 \text{ J}$$

Step 4 · Set the direction

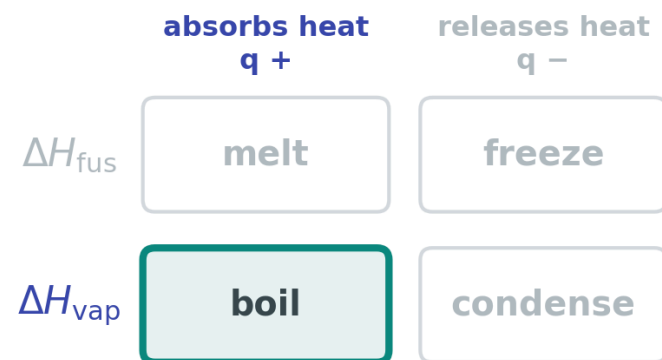
 **Sense check:** Boiling absorbs heat: $q = +45,180 \text{ J}$ (45.2 kJ). Same 20.0 g would take only 6,700 J to melt: vaporizing costs far more. ✓

✓ Worked example 2: the route on the map

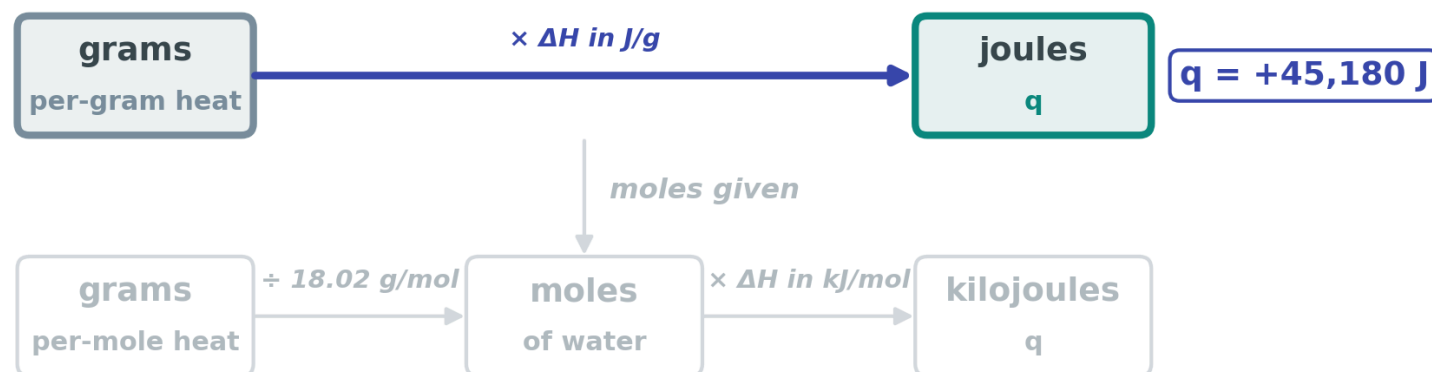
$$q = \text{mass} \times \Delta H_{\text{vap}}$$

given: 20.0 g water at 100 °C · found: $q = +45,180 \text{ J}$

Steps 1, 2 and 4 · which ΔH , which sign



Step 3 · the route



🧠 **Sense check:** Boiling picks ΔH_{vap} . Same top lane as melting; only the factor changed. ✓

Your turn: melt more ice

$$q = \text{mass} \times \Delta H_{\text{fus}}$$

given: 40.0 g ice at 0 °C · $\Delta H_{\text{fus}} = 335 \text{ J/g}$ · wanted: q

40.0 g of ice at 0 °C melts to water. Fill in the heat of fusion, then compute.

$$40.0 \text{ g} \times \frac{\text{ } \text{J}}{1 \text{ g}} = \text{ } \text{J}$$

$$40.0 \text{ g} \times \frac{335 \text{ J}}{1 \text{ g}} = \mathbf{13,400 \text{ J}}$$

 **Sense check:** 335 J melts one gram, so 40.0 g take $40.0 \times 335 = 13,400 \text{ J}$ (13.4 kJ), all at 0 °C. ✓

⚠ Where this goes wrong

$$q = \text{mass} \times \Delta H_{\text{fus}}$$

$$60.0 \text{ g ice at } 0^\circ\text{C} \cdot \Delta H_{\text{fus}} = 335 \text{ J/g} \cdot \text{correct } q = 20,100 \text{ J}$$

Leaving out the mass. 335 J melts a single gram. The sample has 60.0 of them. Scale it up: $60.0 \text{ g} \times 335 \text{ J/g} = 20,100 \text{ J}$.

Dividing by the heat of fusion. $60.0 \div 335 = 0.179$, in units of g^2/J . Nothing cancels. Write the factor so grams cancel: $60.0 \text{ g} \times (335 \text{ J} / 1 \text{ g})$.

Reporting kilojoules as joules. $60.0 \times 335 = 20,100$, then sliding the decimal gives 20.1. That is the value in kilojoules. In joules it is 20,100 J.

Using the vaporization heat to melt. Melting uses $\Delta H_{\text{fus}} = 335 \text{ J/g}$, not $\Delta H_{\text{vap}} = 2259 \text{ J/g}$. $60.0 \times 2259 = 135,540 \text{ J}$ is the heat to boil the water, not melt the ice.

 Practice 2

$$q = \text{mass} \times \Delta H_{\text{vap}}$$

given: $5.00 \times 10^4 \text{ J}$ absorbed by water at 100°C · $\Delta H_{\text{vap}} = 2259 \text{ J/g}$ · wanted: mass boiled away

A kettle delivers $5.00 \times 10^4 \text{ J}$ to water already boiling at 100°C . What mass of water, in grams, boils away? (ΔH_{vap} of water: 2259 J/g)

- A. 22.1
- B. 149
- C. 1.20×10^4
- D. 1.13×10^8

✓ Practice 2 answer: A

$$q = \text{mass} \times \Delta H_{\text{vap}}$$

given: $5.00 \times 10^4 \text{ J}$ absorbed at 100°C · $\Delta H_{\text{vap}} = 2259 \text{ J/g}$ · wanted: g

$$5.00 \times 10^4 \text{ J} \times \frac{1 \text{ g}}{2259 \text{ J}} = 22.1 \text{ g} \cdot \text{answer A}$$

The heat is given, so ΔH_{vap} enters upside down: J on the bottom, so joules cancel. B used the heat of fusion: $5.00 \times 10^4 \div 335 = 149 \text{ g}$ is the ice this heat would melt, not the water it boils. C used water's specific heat: $5.00 \times 10^4 \div 4.184 = 1.20 \times 10^4$, but a plateau has no ΔT , so c does not apply. D kept the factor right side up: $5.00 \times 10^4 \times 2259 = 1.13 \times 10^8$, in J^2/g , nothing cancels.

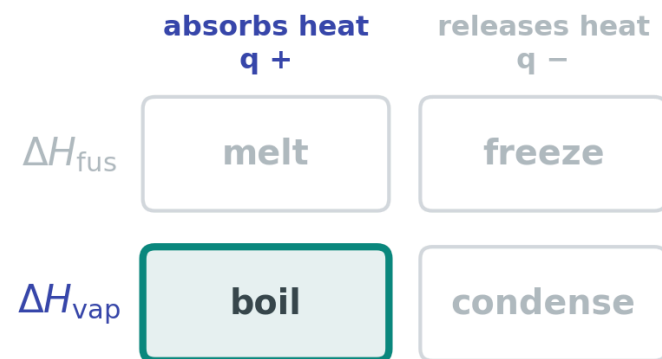
 **Sense check:** Each gram takes 2259 J to boil, so 50,000 J boils a little over 20 g. ✓

✓ Practice 2: the route on the map

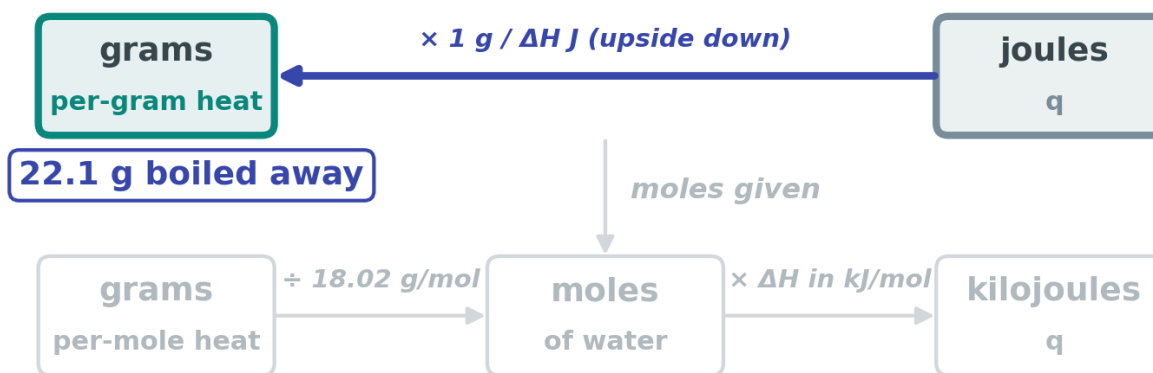
$$q = \text{mass} \times \Delta H_{\text{vap}}$$

given: $5.00 \times 10^4 \text{ J}$ absorbed at 100°C · found: 22.1 g boiled away

Steps 1, 2 and 4 · which ΔH , which sign



Step 3 · the route



 **Sense check:** The heat was given, so the top lane runs backward: ΔH_{vap} upside down, joules cancel, grams remain. ✓



Worked example 3: a steam burn

$$q = \text{mass} \times \Delta H_{\text{vap}}$$

given: 8.00 g steam at 100 °C → water at 100 °C · $\Delta H_{\text{vap}} = 2259 \text{ J/g}$ · wanted: heat released

8.00 g of steam at 100 °C condenses on skin and releases heat. This is why a steam burn is so severe. How much heat comes out?

A common first attempt: add a $q = \text{mass} \times c \times \Delta T$ term for the temperature. Test it.

✓ Worked example 3: solution

$$q = \text{mass} \times \Delta H_{\text{vap}}$$

8.00 g steam · condenses at 100 °C → water at 100 °C · wanted: heat released

A common first attempt

$$m \cdot c \cdot \Delta T = 8.00 \text{ g} \times 4.184 \text{ J/g} \cdot ^\circ\text{C} \times (100 - 100) ^\circ\text{C} = \mathbf{0 \text{ J}}$$

The steam condenses at 100 °C into water at 100 °C. $\Delta T = 0$, so the $m \cdot c \cdot \Delta T$ term adds nothing.

Step 1 · Name the phase change

Step 2 · Pick its ΔH

Condensing uses the heat of vaporization, $\Delta H_{\text{vap}} = 2259 \text{ J/g}$, the same value as boiling.

 **Sense check:** No temperature change means no $m \cdot c \cdot \Delta T$ term. The phase-change heat is the whole answer. ✓

✓ Worked example 3: heat released

$$q = \text{mass} \times \Delta H_{\text{vap}}$$

$$8.00 \text{ g steam condensing at } 100 \text{ }^{\circ}\text{C} \cdot \Delta H_{\text{vap}} = 2259 \text{ J/g}$$

Step 3 • Multiply

$$8.00 \text{ g} \times \frac{2259 \text{ J}}{1 \text{ g}} = 18,072 \text{ J}$$

Step 4 • Set the direction

Heat leaves the steam as it condenses, so q is negative: $q = -18,072 \text{ J}$.

 **Sense check:** Condensing just 8.00 g of steam dumps 18,072 J (18.1 kJ) into the skin, all at 100 °C before the water even starts to cool. That is why steam burns are severe. ✓

✓ Worked example 3: the route on the map

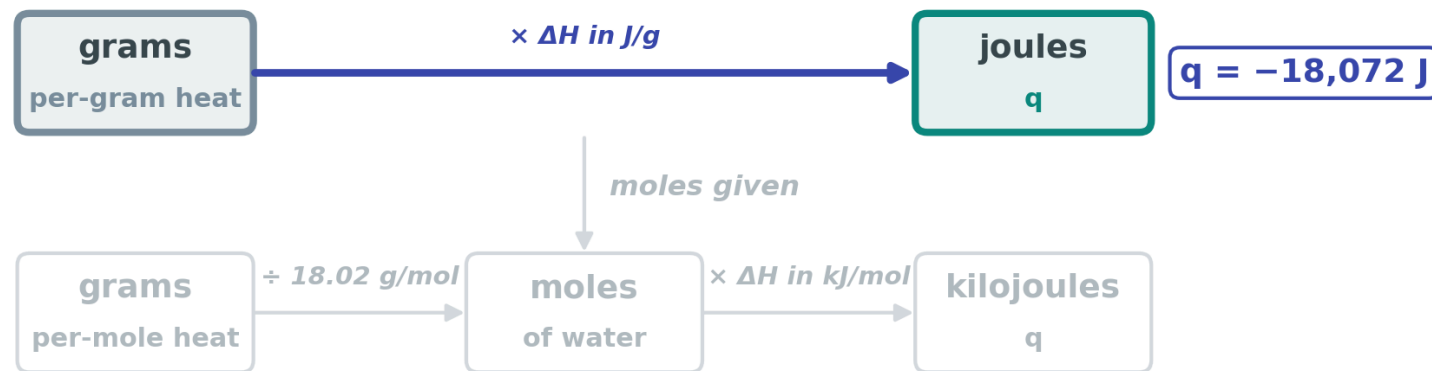
$$q = \text{mass} \times \Delta H_{\text{vap}}$$

given: 8.00 g steam condenses at 100 °C · found: $q = -18,072 \text{ J}$

Steps 1, 2 and 4 · which ΔH , which sign

	absorbs heat $q +$	releases heat $q -$
ΔH_{fus}	melt	freeze
ΔH_{vap}	boil	condense

Step 3 · the route



 **Sense check:** Condensing sits in the releases column: ΔH_{vap} with a minus sign. The route is the top lane, with no $m \cdot c \cdot \Delta T$ anywhere. ✓

 Practice 3

$$q = \text{mass} \times \Delta H$$

given: 45.0 g water at 0 °C freezes · $\Delta H_{\text{fus}} = 335 \text{ J/g}$ · $\Delta H_{\text{vap}} = 2259 \text{ J/g}$

An ice-cube tray holds **45.0 g** of water at 0 °C, and all of it freezes. What is q for the water, sign included, in joules?

- A. 1.51×10^4
- B. -1.02×10^5
- C. -1.51×10^4
- D. -0.134

✓ Practice 3 answer: C

$$q = \text{mass} \times \Delta H_{\text{fus}}$$

freezing is melting reversed: the fusion heat applies, and heat leaves the water

$$45.0 \text{ g} \times \frac{335 \text{ J}}{1 \text{ g}} = 15,075 \text{ J} \rightarrow q = -1.51 \times 10^4 \text{ J} \cdot \text{answer C}$$

A dropped the sign: freezing releases heat, so q for the water is negative. B used the heat of vaporization: $-(45.0 \times 2259) = -1.02 \times 10^5$, but nothing boils or condenses. D divided by the heat of fusion: $45.0 \div 335 = 0.134$, and grams do not cancel.

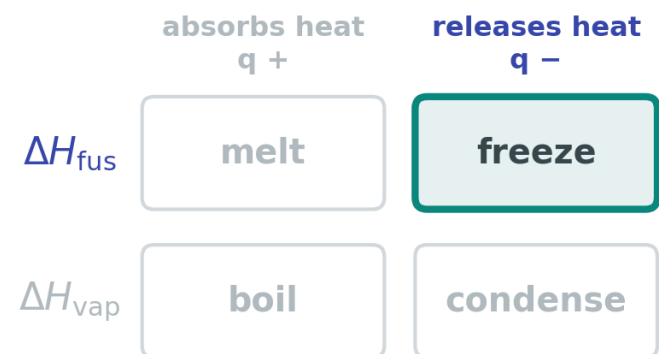
 **Sense check:** Melting the same 45.0 g would absorb $+1.51 \times 10^4 \text{ J}$. Freezing hands that heat back, so $q = -1.51 \times 10^4 \text{ J}$. ✓

✓ Practice 3: the route on the map

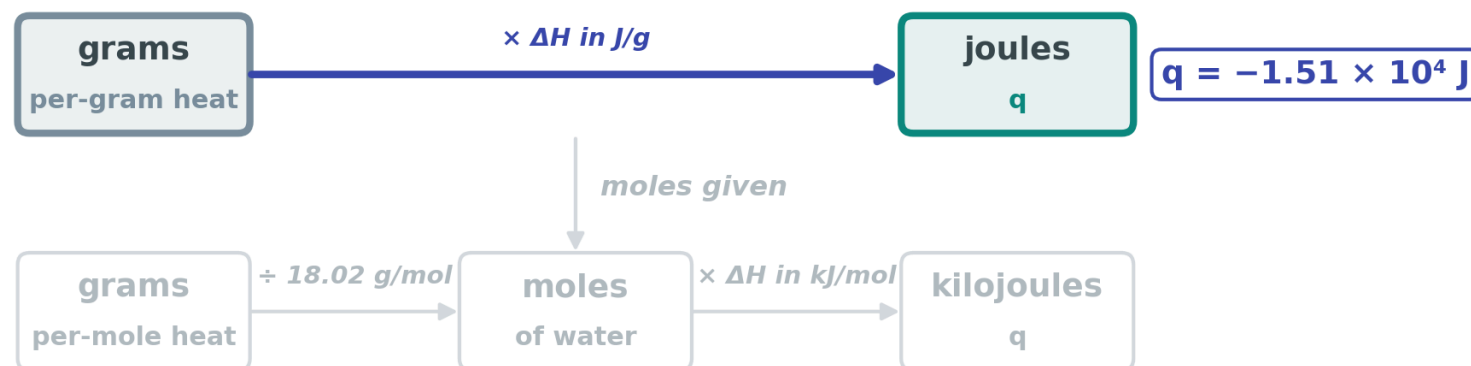
$$q = \text{mass} \times \Delta H_{\text{fus}}$$

given: 45.0 g water at 0 °C freezes · found: $q = -1.51 \times 10^4 \text{ J}$

Steps 1, 2 and 4 · which ΔH , which sign



Step 3 · the route



🧠 **Sense check:** Freezing picks ΔH_{fus} and a minus sign. Grams in with a per-gram heat: the top lane, one factor. ✓



Worked example 4: melting by the molar route

$$q = n \times \Delta H_{\text{fus}}$$

given: 60.0 g ice at 0 °C · $\Delta H_{\text{fus}} = 6.02 \text{ kJ/mol}$ · molar mass of water 18.02 g/mol · wanted: q in kJ

60.0 g of ice at 0 °C melts to water. Find the heat with the molar heat of fusion, **6.02 kJ/mol**. The heat is per mole, so the grams must become moles first.

✓ Worked example 4: solution

$$q = n \times \Delta H_{\text{fus}}$$

given: 60.0 g ice at 0 °C · $\Delta H_{\text{fus}} = 6.02 \text{ kJ/mol}$ · molar mass of water 18.02 g/mol

Step 1 · Name the phase change

Step 2 · Pick its ΔH

Step 3 · Multiply

$$60.0 \text{ g} \times \frac{1 \text{ mol}}{18.02 \text{ g}} \times \frac{6.02 \text{ kJ}}{1 \text{ mol}} = 20.0 \text{ kJ}$$

Step 4 · Set the direction

The per-gram route on the same sample: $60.0 \text{ g} \times 335 \text{ J/g} = 20,100 \text{ J} = 20.1 \text{ kJ}$. Two routes, one heat, agreeing to the rounding of the constants.

 **Sense check:** Melting absorbs heat: $q = +20.0 \text{ kJ}$. 3.33 mol of ice at 6.02 kJ each is about 20 kJ, and the 335 J/g route lands on the same number. ✓

✓ Worked example 4: the route on the map

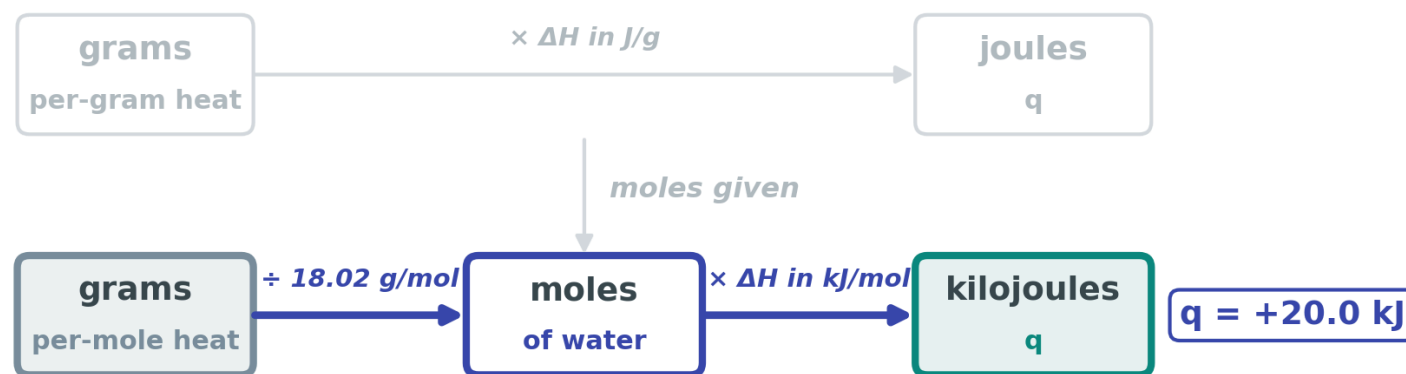
$$q = n \times \Delta H_{\text{fus}}$$

given: 60.0 g ice at 0 °C · found: $q = +20.0 \text{ kJ}$

Steps 1, 2 and 4 · which ΔH , which sign



Step 3 · the route



 **Sense check:** Grams given with a heat per mole: the bottom lane, molar mass first, then ΔH_{fus} . Two factors. ✓

Take-home: a phase change has no ΔT

temperature changes, one phase: $q = m \cdot c \cdot \Delta T$
warming or cooling within a solid, liquid, or gas

temperature constant, changing phase: $q = \text{mass} \times \Delta H$ or $q = n \times \Delta H$
melting, freezing, boiling, condensing. $\Delta T = 0$, so no $m \cdot c \cdot \Delta T$ term

During a phase change the temperature holds, so $\Delta T = 0$ and the $m \cdot c \cdot \Delta T$ term is zero. Use ΔH alone. The two never combine within one phase change.



Practice 4

$$q = n \times \Delta H$$

given: 90.0 g water boiled away at 100 °C · $\Delta H_{\text{fus}} = 6.02 \text{ kJ/mol}$ · $\Delta H_{\text{vap}} = 40.7 \text{ kJ/mol}$ · water 18.02 g/mol

A pasta pot at a rolling boil loses **90.0 g** of water to steam. How much heat, in kJ, did that water absorb?

- A. 30.1
- B. 3.66×10^3
- C. 0.123
- D. 4.99
- E. 203

✓ Practice 4 answer: E

$$q = n \times \Delta H_{\text{vap}}$$

boiling: the vaporization heat applies · 90.0 g water · 18.02 g/mol · 40.7 kJ/mol

Two conversion factors are needed.

$$90.0 \text{ g} \times \frac{1 \text{ mol}}{18.02 \text{ g}} \times \frac{40.7 \text{ kJ}}{1 \text{ mol}} = 203 \text{ kJ} \cdot \text{answer E}$$

A used the heat of fusion: $4.99 \times 6.02 = 30.1$. B skipped the molar mass: $90.0 \times 40.7 = 3.66 \times 10^3$, as if each gram were a mole. C put the molar heat upside down: $4.99 \div 40.7 = 0.123$. D stopped at moles: 4.99 mol, one factor short.

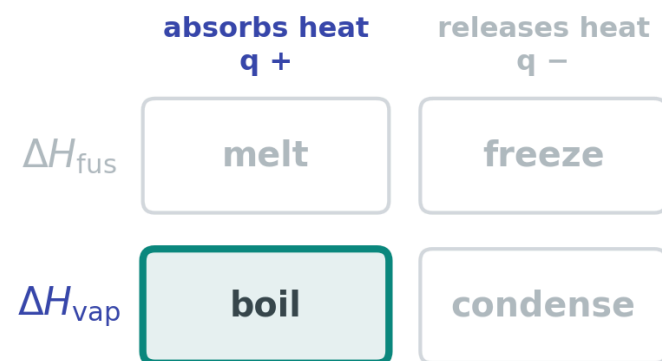
 **Sense check:** Boiling absorbs heat: $q = +203 \text{ kJ}$. About 5 mol at about 41 kJ each is about 200 kJ. ✓

✓ Practice 4: the route on the map

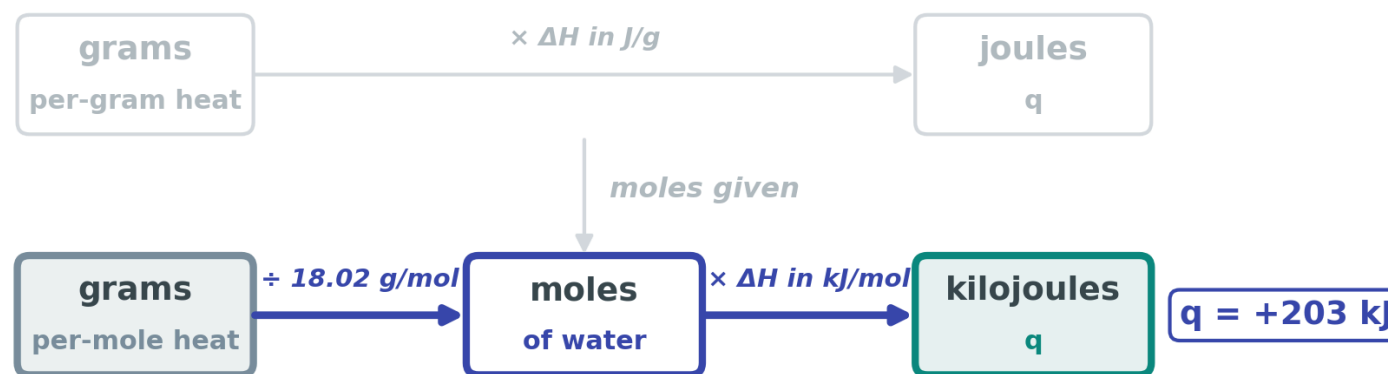
$$q = n \times \Delta H_{\text{vap}}$$

given: 90.0 g water boiled away at 100 °C · found: $q = +203 \text{ kJ}$

Steps 1, 2 and 4 · which ΔH , which sign



Step 3 · the route



 **Sense check:** Grams given with a heat per mole: the bottom lane, molar mass first, then ΔH_{vap} . Two factors. ✓

 Practice 5

$$q = n \times \Delta H$$

given: 15.0 kJ removed from liquid water at 0 °C · $\Delta H_{\text{fus}} = 6.02 \text{ kJ/mol}$ · $\Delta H_{\text{vap}} = 40.7 \text{ kJ/mol}$ · water
18.02 g/mol · wanted: g of ice

A freezer removes **15.0 kJ** of heat from liquid water at 0 °C. What mass of ice, in grams, forms?

- A. 6.64
- B. 44.9
- C. 0.138
- D. 2.49

✓ Practice 5 answer: B

$$q = n \times \Delta H_{\text{fus}}$$

freezing is melting reversed: the fusion heat applies · 15.0 kJ released by the water · 18.02 g/mol

$$15.0 \text{ kJ} \times \frac{1 \text{ mol}}{6.02 \text{ kJ}} \times \frac{18.02 \text{ g}}{1 \text{ mol}} = 44.9 \text{ g} \cdot \text{answer B}$$

The heat is given, so ΔH_{fus} enters upside down and kJ cancels. A picked the vaporization heat: $15.0 \div 40.7 \times 18.02 = 6.64 \text{ g}$, but no boiling or condensing happens here. C divided by the molar mass: $2.49 \div 18.02 = 0.138 \text{ g}$. D stopped at moles: 2.49 mol of water, one factor short of grams.

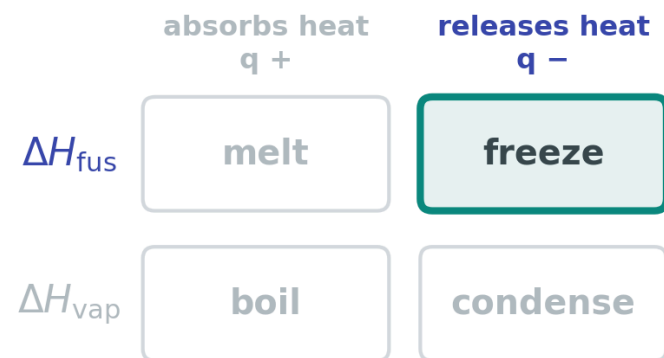
 **Sense check:** Freezing releases heat, so q for the water is -15.0 kJ ; the mass of ice is positive. 2.49 mol at 18.02 g each is about 45 g. ✓

✓ Practice 5: the route on the map

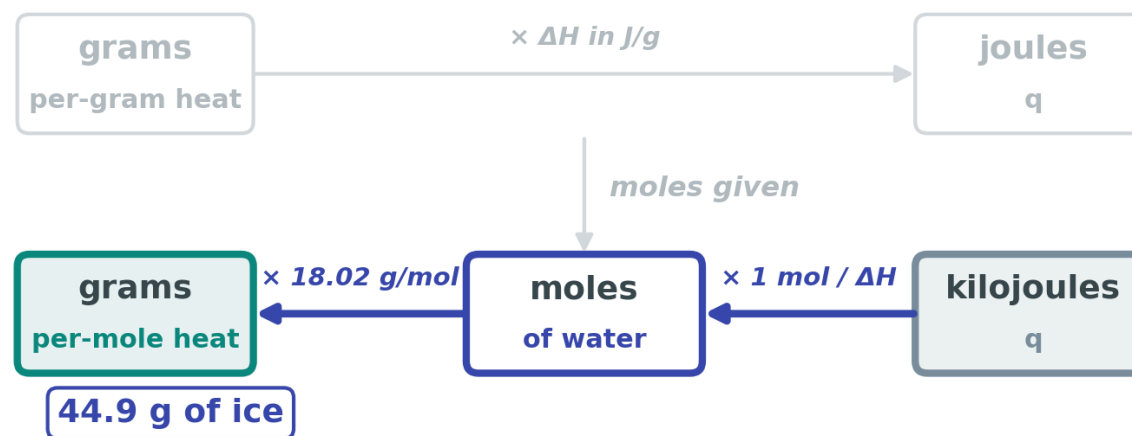
$$q = n \times \Delta H_{\text{fus}}$$

given: 15.0 kJ removed from water at 0 °C · found: 44.9 g of ice

Steps 1, 2 and 4 · which ΔH , which sign



Step 3 · the route



🧠 **Sense check:** Freezing picks ΔH_{fus} . The heat was given, so the bottom lane runs backward: kilojoules to moles, then moles to grams. ✓



Practice 6

$$q = \text{mass} \times \Delta H$$

given: 28.0 g boiled vs 28.0 g melted · $\Delta H_{\text{fus}} = 335 \text{ J/g}$ · $\Delta H_{\text{vap}} = 2259 \text{ J/g}$ · wanted: difference

How much more heat, in joules, does it take to boil away **28.0 g** of water at 100 °C than to melt 28.0 g of ice at 0 °C?

- A. 7.26×10^4
- B. 6.74
- C. 6.33×10^4
- D. 5.39×10^4

✓ Practice 6 answer: D

$q = \text{mass} \times \Delta H$, once for each change

28.0 g · boil: $\Delta H_{\text{vap}} = 2259 \text{ J/g}$ · melt: $\Delta H_{\text{fus}} = 335 \text{ J/g}$ · wanted: boil minus melt

$$28.0 \text{ g} \times \frac{2259 \text{ J}}{1 \text{ g}} = 63,252 \text{ J} \quad \cdot \quad 28.0 \text{ g} \times \frac{335 \text{ J}}{1 \text{ g}} = 9,380 \text{ J}$$

$$63,252 \text{ J} - 9,380 \text{ J} = \mathbf{5.39 \times 10^4 \text{ J} \cdot \text{answer D}}$$

A added the two heats: $63,252 + 9,380 = 7.26 \times 10^4 \text{ J}$ is the cost of both changes, not the gap. B divided the heats: $2259 \div 335 = 6.74$ says how many times more, not how many joules more. C stopped at the boiling heat: $28.0 \times 2259 = 6.33 \times 10^4 \text{ J}$, with the melt never subtracted.

 **Sense check:** Each gram costs $2259 - 335 = 1924 \text{ J}$ more to boil than to melt. 28.0 g of that is about 54,000 J. ✓

 Practice 7

$$q = n \times \Delta H$$

given: 62.0 g C₂H₅OH boiled · ΔH_{vap} of ethanol = 38.6 kJ/mol · wanted: q in kJ

A still boils off **62.0 g** of ethanol, C₂H₅OH, at its boiling point. How much heat, in kJ, does the ethanol absorb?

- A. 51.9
- B. 2.39×10^3
- C. 133
- D. 1.10×10^5

✓ Practice 7 answer: A

$$q = n \times \Delta H_{\text{vap}}$$

boiling: the vaporization heat applies · 62.0 g C₂H₅OH · 38.6 kJ/mol · molar mass from the formula

Two conversion factors are needed, and the first one is ethanol's molar mass: $2(12.01) + 6(1.008) + 16.00 = 46.07 \text{ g/mol}$.

$$62.0 \text{ g} \times \frac{1 \text{ mol}}{46.07 \text{ g}} \times \frac{38.6 \text{ kJ}}{1 \text{ mol}} = 51.9 \text{ kJ} \cdot \text{answer A}$$

B skipped the molar mass: $62.0 \times 38.6 = 2.39 \times 10^3$, as if each gram were a mole. C used water's molar mass: $62.0 \div 18.02 \times 38.6 = 133$, but the liquid is ethanol. D put the molar mass upside down: $62.0 \times 46.07 \times 38.6 = 1.10 \times 10^5$, and grams do not cancel.

 **Sense check:** Boiling absorbs heat: $q = +51.9 \text{ kJ}$. About 1.35 mol at about 39 kJ each is about 52 kJ. ✓



Practice 8

water (H_2O) vs hydrogen sulfide (H_2S), each at its boiling point

H_2O : 18.02 g/mol, $\Delta H_{\text{vap}} = 40.7 \text{ kJ/mol}$ · H_2S : 34.08 g/mol, $\Delta H_{\text{vap}} = 18.7 \text{ kJ/mol}$

Why is water's heat of vaporization more than twice that of H_2S ?

- A. Water's O-H bonds break as it boils
- B. H_2S is nonpolar, so dispersion is its only force
- C. Water molecules hydrogen bond to one another
- D. H_2S molecules hydrogen bond, but more weakly
- E. Both: water hydrogen bonds, and its O-H bonds break

✓ Practice 8 answer: C

water: hydrogen bonding · H₂S: dipole-dipole · answer C
boiling pulls whole molecules apart · 40.7 vs 18.7 kJ/mol · 18.02 vs 34.08 g/mol

Water's H sits on O, so its molecules hydrogen bond. H₂S is bent and polar, but its H sits on S: dipole-dipole is its strongest force. Pulling hydrogen-bonded molecules apart costs more heat per mole.

A broke the wrong bonds: boiling separates whole H₂O molecules, and every O-H bond survives into the steam. B missed the bent shape: H₂S is polar, so it has dipole-dipole on top of dispersion. D let sulfur qualify; an H on S forms no hydrogen bond. E kept the right half but added A's bond-breaking claim.

 **Sense check:** Water is the lighter molecule, yet it takes 2.18 times the heat per mole. The force type decided it, not the mass. ✓

Check yourself

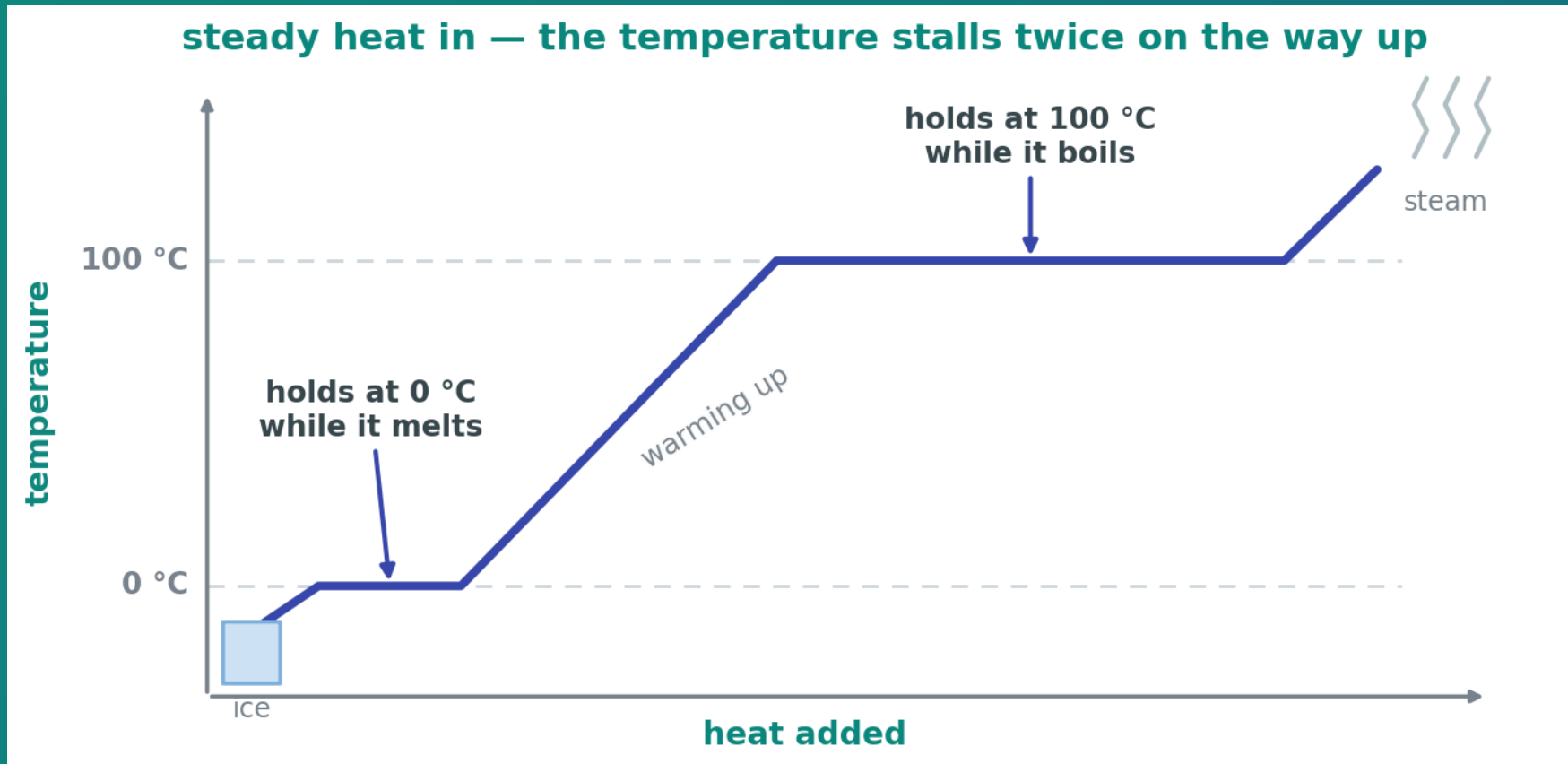
1. A block of ice at 0 °C melts to water at 0 °C. What happens to the temperature while it melts, and where does the heat go?
2. Which is larger for water, the heat of fusion or the heat of vaporization, and why?

Melting and boiling are the flat steps of a heating curve. Between those steps the temperature climbs, and there $q = m \cdot c \cdot \Delta T$ takes over. The full curve chains both kinds of heat, segment by segment.

6 · Heating & Cooling Curves

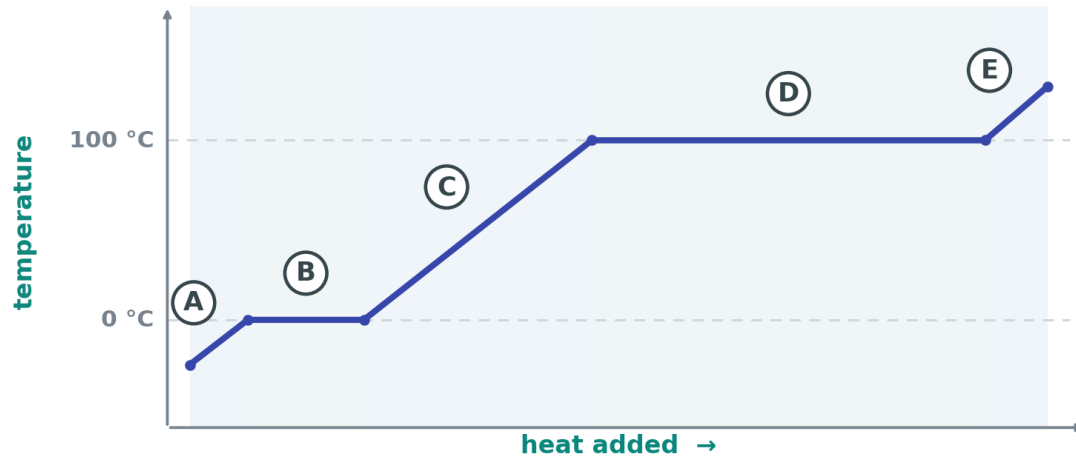
Break a heating path into segments, use $q = m \cdot c \cdot \Delta T$ for each slope and the phase-change energy for each plateau, and add them for the total heat.

From the freezer to a rolling boil



Heat a block of ice steadily. Temperature climbs, holds at 0 °C while it melts, climbs, then holds at 100 °C while it boils.

Reading a heating curve, one segment at a time

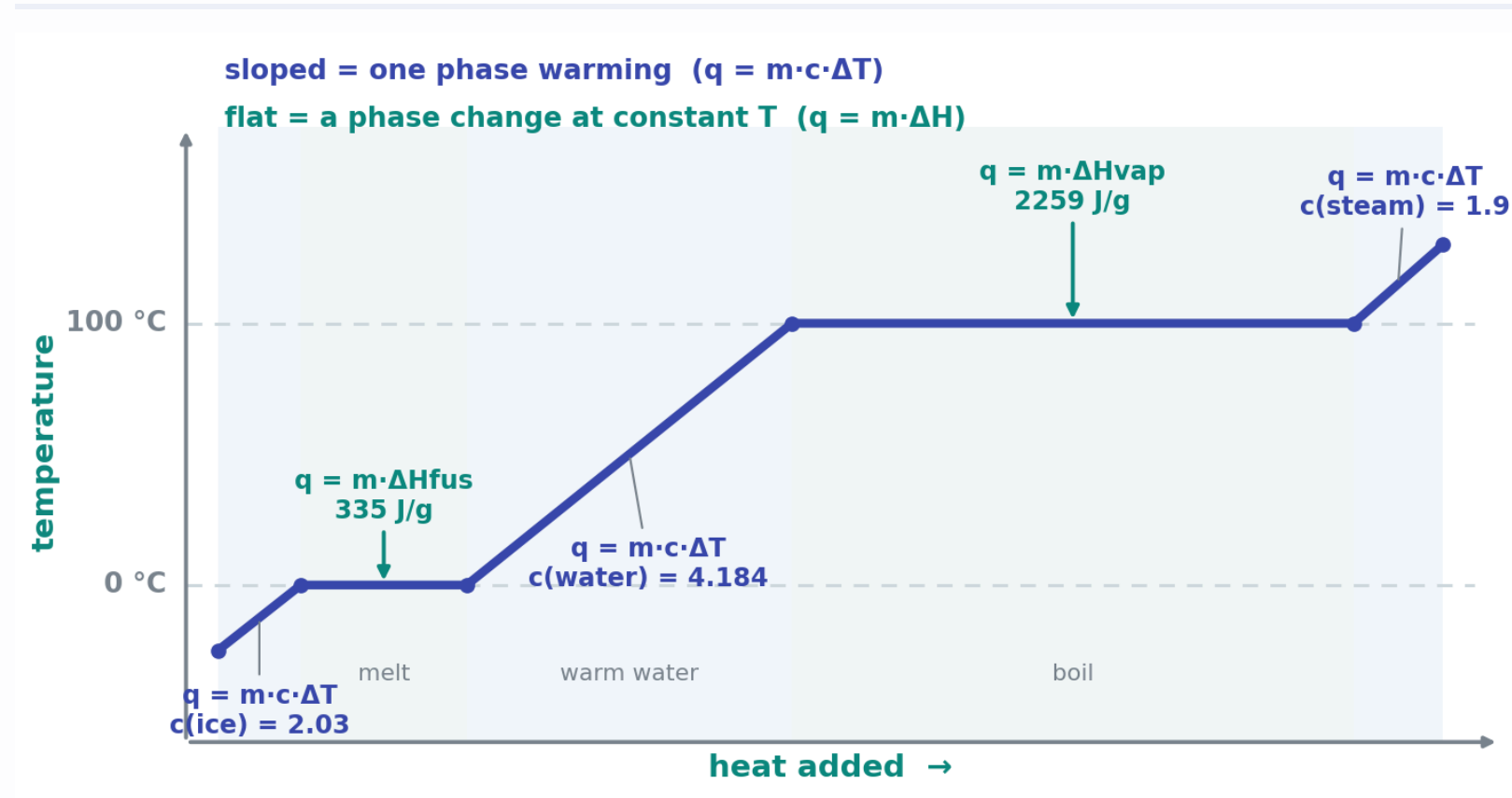


Heat flows in steadily. The temperature climbs while one phase warms and holds while the phase changes. Which letter shows ice and liquid water together? Which shows liquid water warming?

B: ice and liquid water together, melting at 0 °C · C: liquid water warming from 0 to 100 °C

read right to left, the same path is a cooling curve: steam condenses along D, water freezes along B

Warming and phase changes alternate



Heating a substance alternates between warming one phase (a sloped step, $q = m \cdot c \cdot \Delta T$) and changing the phase (a flat step, phase-change energy). The total heat is the sum of every step.

Two kinds of segment, two equations

sloped segment: one phase warming

$q = m \cdot c \cdot \Delta T$ · uses that phase's specific heat c

flat plateau: a phase change at constant T

$q = m \cdot \Delta H$ · the temperature does not move, so there is no ΔT

Read the graph one segment at a time. A slope warms a single phase. A plateau holds the temperature fixed while the phase changes. Each segment needs its own equation.

Water's constants for each segment

slopes: $q = m \cdot c \cdot \Delta T$

$$c(\text{ice}) = 2.03 \cdot c(\text{liquid water}) = 4.184 \cdot c(\text{steam}) = 1.9 \text{ J/g}\cdot^\circ\text{C}$$

plateaus: $q = m \cdot \Delta H$

$$\Delta H_{\text{fus}} = 335 \text{ J/g at } 0^\circ\text{C} \cdot \Delta H_{\text{vap}} = 2259 \text{ J/g at } 100^\circ\text{C}$$

Each phase carries its own specific heat. Each phase change carries its own energy. Ice and steam sit near 2 J/g·°C; only liquid water earns 4.184.



The method

1. **Identify each segment.** Each slope and each plateau is one piece.
2. **Compute each piece.** A slope uses $q = m \cdot c \cdot \Delta T$ with that phase's c . A plateau uses the phase-change energy, ΔH_{fus} or ΔH_{vap} .
3. **Add every piece** for the total.



Guided example: water to steam

total q = warm water + boil

given: 40.0 g water at 80.0 °C → steam at 100 °C · $c(\text{water}) = 4.184 \text{ J/g} \cdot ^\circ\text{C}$ · $\Delta H_{\text{vap}} = 2259 \text{ J/g}$ ·

wanted: q

A kettle holds **40.0 g** of water at **80.0 °C**. It heats until all of the water has boiled away as steam at 100 °C. How much heat does that take?

Find the start and the end on the curve, then follow it between them.

✓ Guided example: solution

total q = warm water + boil

given: 40.0 g water at 80.0 °C → steam at 100 °C · $c(\text{water}) = 4.184 \text{ J/g} \cdot \text{°C}$ · $\Delta H_{\text{vap}} = 2259 \text{ J/g}$

Step 1 · Identify each segment

Step 2 · Compute each piece

$$\text{warm water: } 40.0 \text{ g} \times \frac{4.184 \text{ J}}{1 \text{ g} \cdot \text{°C}} \times 20.0 \text{ °C} = 3347 \text{ J} \cdot \text{boil: } 40.0 \text{ g} \times \frac{2259 \text{ J}}{1 \text{ g}} = 90,360 \text{ J}$$

Step 3 · Add every piece

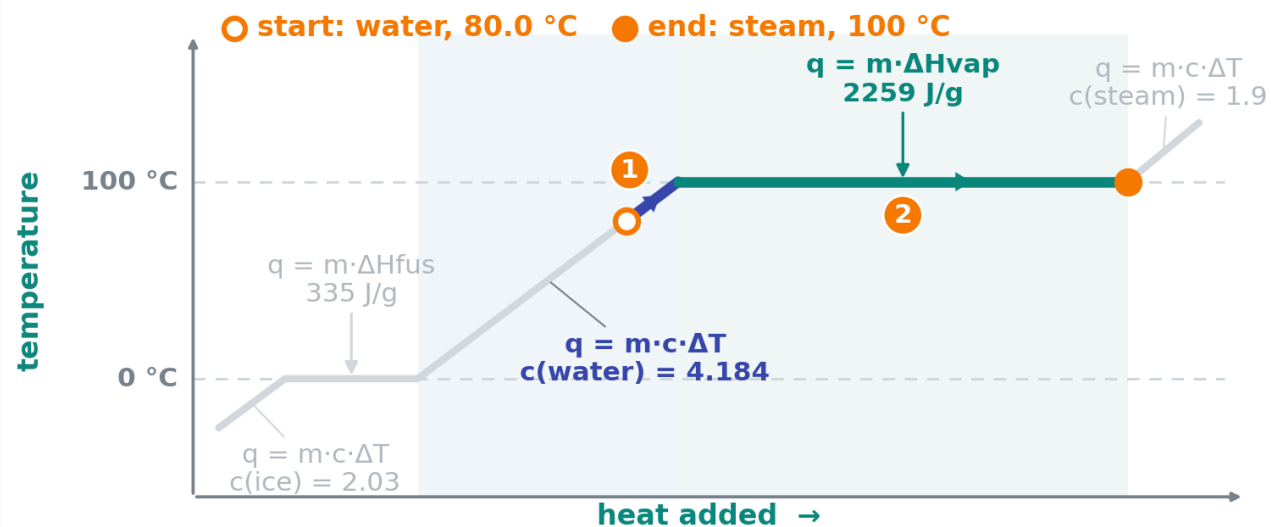
$$q = 3347 \text{ J} + 90,360 \text{ J} = 93,707 \text{ J} = 9.37 \times 10^4 \text{ J}$$

 **Sense check:** Boiling costs 27 times the warming. Almost all the heat goes into the plateau. ✓

✓ Guided example: the route on the curve

total q = warm water + boil

given: 40.0 g water, 80.0 °C → steam, 100 °C · found: $q = 9.37 \times 10^4 \text{ J}$



🧠 **Sense check:** Two pieces lie between the start and the end: one slope, one plateau. ✓

 Practice 1

total q = the sum of every segment crossed

given: ice at $-15\text{ }^{\circ}\text{C}$ $\rightarrow$ liquid water at $60\text{ }^{\circ}\text{C}$ · wanted: the pieces

A snowball at $-15\text{ }^{\circ}\text{C}$ goes into a hot pot and ends as liquid water at $60\text{ }^{\circ}\text{C}$. Which pieces make up the total heat?

- A. warm ice + melt + warm water
- B. melt + warm water
- C. warm ice + warm water
- D. warm ice + melt

✓ Practice 1 answer: A

ice at $-15\text{ }^{\circ}\text{C} \rightarrow$ liquid water at $60\text{ }^{\circ}\text{C}$

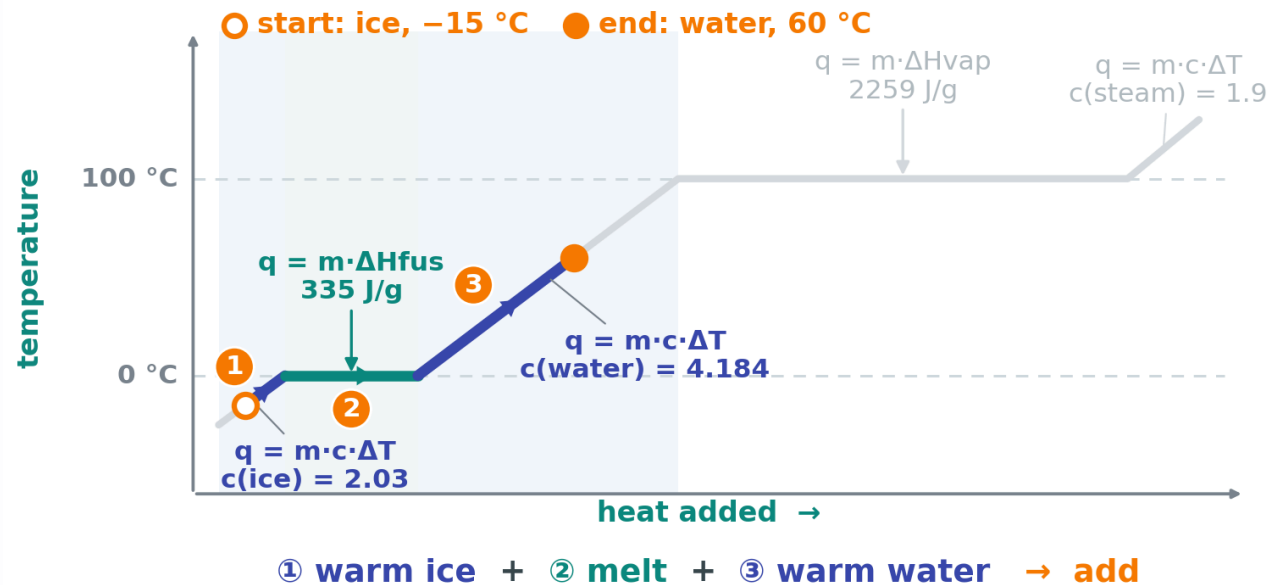
warm ice, $-15 \rightarrow 0\text{ }^{\circ}\text{C}$ · melt at $0\text{ }^{\circ}\text{C}$ · warm water, $0 \rightarrow 60\text{ }^{\circ}\text{C}$ · $60\text{ }^{\circ}\text{C}$ is below $100\text{ }^{\circ}\text{C}$, so nothing boils

B started at the melting point: the ice must first warm from $-15\text{ }^{\circ}\text{C}$ to $0\text{ }^{\circ}\text{C}$. C skipped the plateau: melting takes heat even though the temperature holds. D stopped at the melting point: the water still has to warm to $60\text{ }^{\circ}\text{C}$.

🧠 **Sense check:** Three pieces, answer A: two slopes and the plateau between them. ✓

✓ Practice 1: the route on the curve

ice at $-15\text{ }^{\circ}\text{C}$ → liquid water at $60\text{ }^{\circ}\text{C}$
 three pieces: warm ice · melt · warm water



🧠 **Sense check:** Each segment between the start and the end is one piece. Boiling lies past the end. ✓



Worked example 1: ice at 0 °C to warm water

$$\text{total } q = \text{melt} + \text{warm}$$

given: 30 g ice at 0 °C → liquid water at 25 °C · $\Delta H_{\text{fus}} = 335 \text{ J/g}$ · $c(\text{water}) = 4.184 \text{ J/g}\cdot^\circ\text{C}$ · wanted: q

A **30 g** block of ice, already at 0 °C, is heated until it becomes liquid water at 25 °C. How much heat does it take?

Identify each segment, then add the pieces.

✓ Worked example 1: solution

total q = melt + warm

given: 30 g ice at 0 °C → liquid water at 25 °C · $\Delta H_{\text{fus}} = 335 \text{ J/g}$ · $c(\text{water}) = 4.184 \text{ J/g}\cdot^{\circ}\text{C}$

Step 1 · Identify each segment

Step 2 · Compute each piece

$$\text{melt: } 30 \text{ g} \times \frac{335 \text{ J}}{1 \text{ g}} = 10,050 \text{ J} \cdot \text{warm: } 30 \text{ g} \times \frac{4.184 \text{ J}}{1 \text{ g}\cdot^{\circ}\text{C}} \times 25 \text{ }^{\circ}\text{C} = 3138 \text{ J}$$

Step 3 · Add every piece

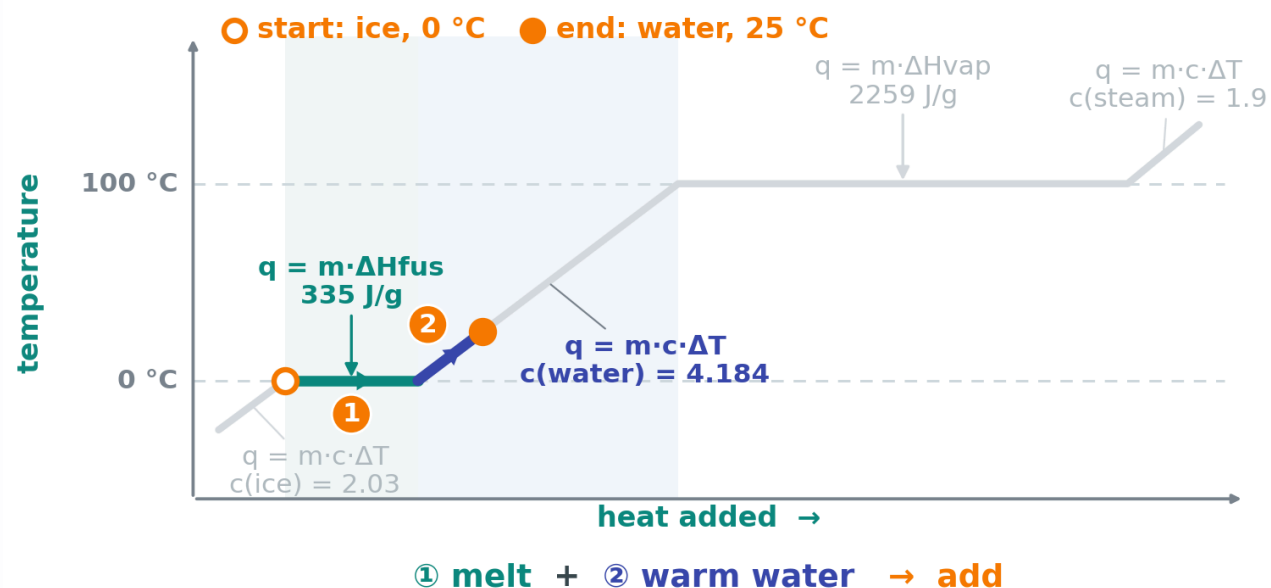
$$q = 10,050 \text{ J} + 3138 \text{ J} = 13,188 \text{ J}$$

 **Sense check:** Melting alone costs 10,050 J, more than warming the liquid 25 °C. The flat step costs more. ✓

✓ Worked example 1: the route on the curve

total $q = \text{melt} + \text{warm}$

given: 30 g ice at 0 °C → liquid water at 25 °C · found: $q = 13,188 \text{ J}$



🧠 **Sense check:** The ice starts on the plateau, so no ice warms. Two pieces: melt, then warm water. ✓



Worked example 2: melt, then warm to 40 °C

$$\text{total } q = \text{melt} + \text{warm}$$

given: 45 g ice at 0 °C → liquid water at 40 °C · $\Delta H_{\text{fus}} = 335 \text{ J/g}$ · $c(\text{water}) = 4.184 \text{ J/g}\cdot^\circ\text{C}$ · wanted: q

A **45 g** block of ice at 0 °C is melted and then warmed to 40 °C.

A common first attempt: the sample ends 40 °C warmer, so multiply the melting heat by 40 as well. Test it.

✓ Worked example 2: the melting step

total q = melt + warm

given: 45 g ice at 0 °C → liquid water at 40 °C · $\Delta H_{\text{fus}} = 335 \text{ J/g}$ · $c(\text{water}) = 4.184 \text{ J/g}\cdot^\circ\text{C}$

A common first attempt

$$\text{melt: } 45 \text{ g} \times \frac{335 \text{ J}}{1 \text{ g}} \times 40^\circ\text{C} = 603,000 \text{ J} \times$$

Step 1 • Identify each segment

Two pieces: melt at 0 °C, then warm the liquid from 0 °C to 40 °C. Only the warming piece has a ΔT .

 **Sense check:** The melting step holds at 0 °C, so it carries no temperature change. Only the warming step does. ✓

✓ Worked example 2: the two pieces

total q = melt + warm

given: 45 g ice at 0 °C → liquid water at 40 °C · $\Delta H_{\text{fus}} = 335 \text{ J/g}$ · $c(\text{water}) = 4.184 \text{ J/g}\cdot^{\circ}\text{C}$

Step 2 · Compute each piece

$$\text{melt: } 45 \text{ g} \times \frac{335 \text{ J}}{1 \text{ g}} = 15,075 \text{ J} \cdot \text{warm: } 45 \text{ g} \times \frac{4.184 \text{ J}}{1 \text{ g}\cdot^{\circ}\text{C}} \times 40 \text{ }^{\circ}\text{C} = 7531.2 \text{ J}$$

Step 3 · Add every piece

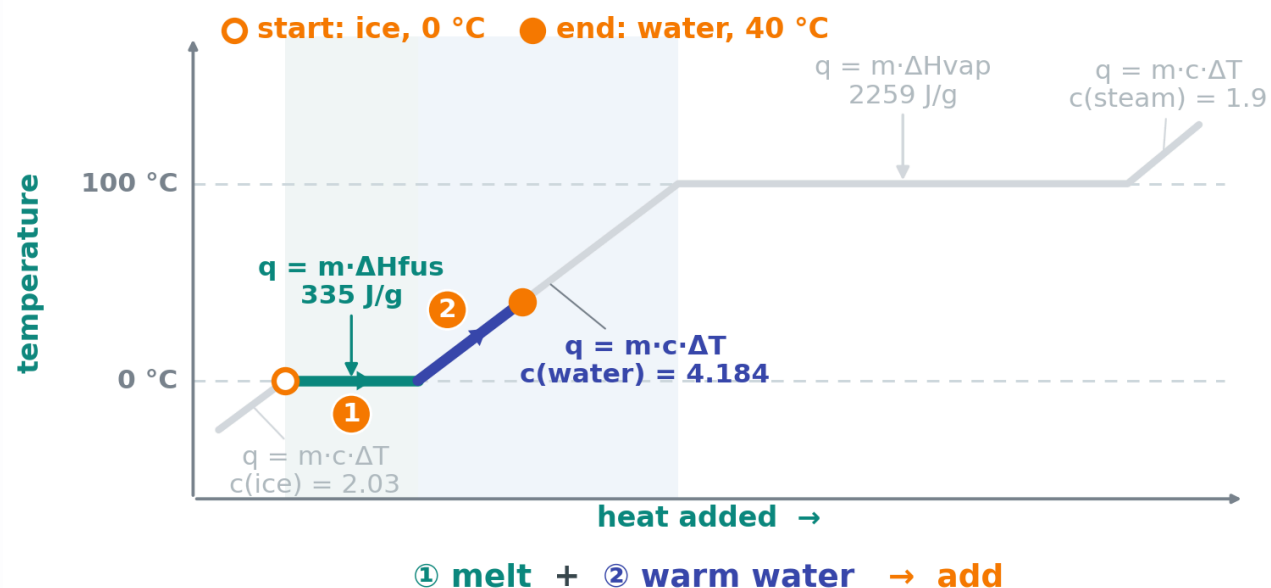
$$q = 15,075 \text{ J} + 7531.2 \text{ J} = 22,606 \text{ J}$$

 **Sense check:** The two pieces add to 22,606 J. The plateau-times- ΔT shortcut, 603,000 J, was about 27 times too large. ✓

✓ Worked example 2: the route on the curve

total $q = \text{melt} + \text{warm}$

given: 45 g ice at 0 °C → liquid water at 40 °C · found: $q = 22,606 \text{ J}$



🧠 **Sense check:** The same two pieces. Only the slope carries a ΔT ; the plateau is $m \cdot \Delta H_{\text{fus}}$ alone. ✓

Take-home: a plateau is not $q = m \cdot c \cdot \Delta T$

melt at 0 °C: correct

$$q = m \cdot \Delta H_{\text{fus}} = 45 \text{ g} \times 335 \text{ J/g} = 15,075 \text{ J} \cdot \text{temperature stays } 0 \text{ }^{\circ}\text{C}$$

treating the plateau as $q = m \cdot c \cdot \Delta T$: wrong

$$45 \text{ g} \times 335 \text{ J/g} \times 40 \text{ }^{\circ}\text{C} = 603,000 \text{ J} \times \cdot \text{there is no } \Delta T \text{ on a plateau}$$

On a flat plateau the temperature is constant, so ΔT is zero. The heat comes from ΔH_{fus} or ΔH_{vap} . A phase-change energy is never multiplied by a temperature change.



Worked example 3: ice at $-20\text{ }^{\circ}\text{C}$ to steam at $120\text{ }^{\circ}\text{C}$

total q = warm ice + melt + warm water + boil + warm steam

given: $20\text{ g} \cdot -20\text{ }^{\circ}\text{C} \rightarrow 120\text{ }^{\circ}\text{C} \cdot c(\text{ice}) 2.03 \cdot c(\text{water}) 4.184 \cdot c(\text{steam}) 1.9\text{ J/g}\cdot^{\circ}\text{C} \cdot \Delta H_{\text{fus}} 335 \cdot \Delta H_{\text{vap}}$
 $2259\text{ J/g} \cdot \text{wanted: } q$

A **20 g** sample starts as ice at $-20\text{ }^{\circ}\text{C}$ and ends as steam at $120\text{ }^{\circ}\text{C}$.

Count the segments between the start and end, then compute and add each one.

✓ Worked example 3: warming and melting

total q = warm ice + melt + warm water + boil + warm steam
 20 g · -20 °C → 120 °C · five segments to cross

Step 1 · Identify each segment

Step 2 · Compute each piece

$$\text{warm ice: } 20 \text{ g} \times \frac{2.03 \text{ J}}{1 \text{ g} \cdot ^\circ\text{C}} \times 20 ^\circ\text{C} = \mathbf{812 \text{ J}} \cdot \text{melt: } 20 \text{ g} \times \frac{335 \text{ J}}{1 \text{ g}} = \mathbf{6700 \text{ J}}$$

$$\text{warm water: } 20 \text{ g} \times \frac{4.184 \text{ J}}{1 \text{ g} \cdot ^\circ\text{C}} \times 100 ^\circ\text{C} = \mathbf{8368 \text{ J}}$$

🧠 **Sense check:** Each slope uses its own phase's c: ice 2.03, water 4.184. The plateaus still to come cost more. ✓

✓ Worked example 3: boiling, then the total

total q = warm ice + melt + warm water + boil + warm steam
 warm ice 812 · melt 6700 · warm water 8368 J so far

Step 2 · Compute each piece

$$\text{boil: } 20 \text{ g} \times \frac{2259 \text{ J}}{1 \text{ g}} = 45,180 \text{ J} \cdot \text{ warm steam: } 20 \text{ g} \times \frac{1.9 \text{ J}}{1 \text{ g} \cdot ^\circ\text{C}} \times 20 ^\circ\text{C} = 760 \text{ J}$$

Step 3 · Add every piece

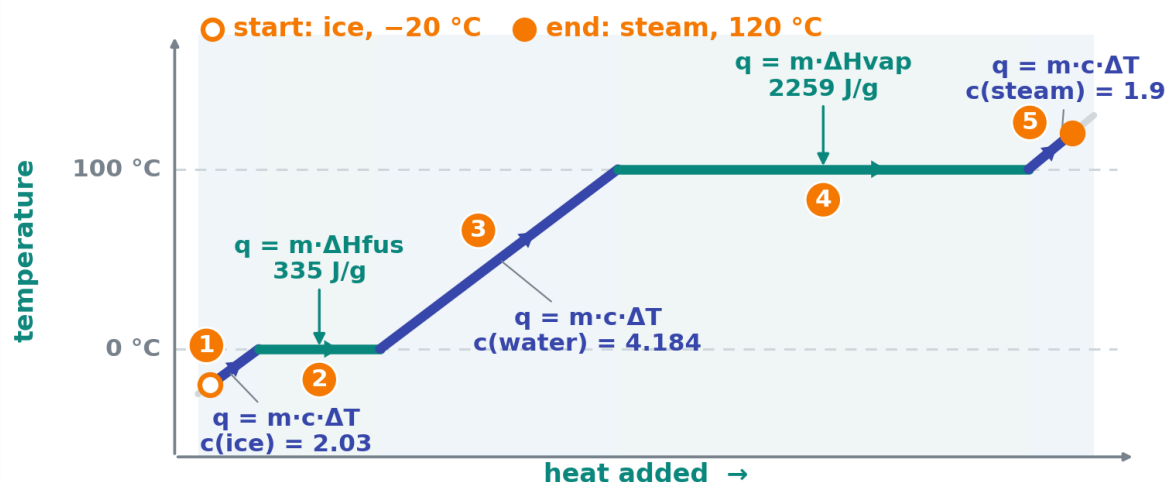
$$q = 812 + 6700 + 8368 + 45,180 + 760 = 61,820 \text{ J}$$

 **Sense check:** Boiling alone is 45,180 J, about three-quarters of the total. Vaporizing water takes the most heat. ✓

✓ Worked example 3: the route on the curve

total q = warm ice + melt + warm water + boil + warm steam

given: 20 g ice at $-20\text{ }^{\circ}\text{C}$ $\rightarrow$ steam at $120\text{ }^{\circ}\text{C}$ · found: $q = 61,820\text{ J}$



① warm ice + ② melt + ③ warm water + ④ boil + ⑤ warm steam $\rightarrow$ add

🧠 **Sense check:** The whole curve: three slopes, each with its own c , and both plateaus. ✓

Plateau heats per mole

$$q = n \cdot \Delta H$$

$$n = \text{mass} \div 18.02 \text{ g/mol} \cdot \Delta H_{\text{fus}} = 6.02 \text{ kJ/mol} \cdot \Delta H_{\text{vap}} = 40.7 \text{ kJ/mol}$$

slopes give J · a per-mole plateau gives kJ

1 kJ = 1000 J · every piece goes into one unit before adding

Plateau heats also come per mole. Grams convert to moles first, and that piece comes out in kilojoules. The slopes still give joules.



Worked example 4: boil, then warm the steam

total q = boil + warm steam

given: 36.0 g water at 100.0 °C → steam at 130.0 °C · $\Delta H_{\text{vap}} = 40.7 \text{ kJ/mol}$ · $c(\text{steam}) = 1.9 \text{ J/g}\cdot^\circ\text{C}$ ·
18.02 g/mol · wanted: q in kJ

36.0 g of water sits at its boiling point, **100.0 °C**. It boils completely, and the steam warms to **130.0 °C**. How much heat does it take, in kJ?

The heat of vaporization is given per mole.

✓ Worked example 4: solution

total q = boil + warm steam

given: 36.0 g water at 100.0 °C → steam at 130.0 °C · $\Delta H_{\text{vap}} = 40.7 \text{ kJ/mol}$ · $c(\text{steam}) = 1.9 \text{ J/g}\cdot^{\circ}\text{C}$ ·
18.02 g/mol

Step 1 · Identify each segment

Step 2 · Compute each piece

$$\text{boil: } 36.0 \text{ g} \times \frac{1 \text{ mol}}{18.02 \text{ g}} \times \frac{40.7 \text{ kJ}}{1 \text{ mol}} = 81.3 \text{ kJ}$$

$$\text{warm steam: } 36.0 \text{ g} \times \frac{1.9 \text{ J}}{1 \text{ g}\cdot^{\circ}\text{C}} \times 30.0 \text{ }^{\circ}\text{C} = 2052 \text{ J}$$

🧠 **Sense check:** Grams became moles before ΔH_{vap} applied. The plateau came out in kJ, the slope in J. ✓

✓ Worked example 4: adding the pieces

total q = boil + warm steam
 boil 81.3 kJ · warm steam 2052 J · wanted: q in kJ

A common first attempt

$$81.3 + 2052 = 2133 \times$$

Step 3 · Add every piece

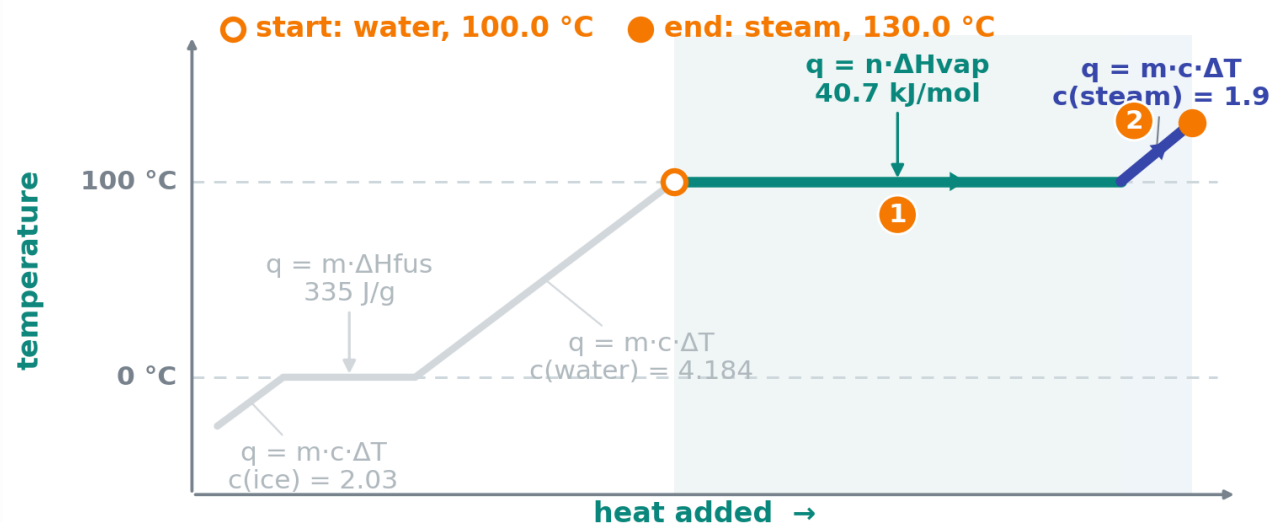
$$2052 \text{ J} \times \frac{1 \text{ kJ}}{1000 \text{ J}} = 2.052 \text{ kJ} \cdot q = 81.3 \text{ kJ} + 2.052 \text{ kJ} = \mathbf{83.4 \text{ kJ}}$$

 **Sense check:** Boiling carries almost all of it: 81.3 of the 83.4 kJ. ✓

✓ Worked example 4: the route on the curve

total $q = \text{boil} + \text{warm steam}$

given: 36.0 g water at 100.0 °C → steam at 130.0 °C · found: $q = 83.4 \text{ kJ}$



① boil + ② warm steam → kJ and J to one unit, then add

🧠 **Sense check:** The per-mole plateau adds two moves: grams to moles, then kJ and J into one unit. ✓

Your turn: 15 g of ice to warm water

total q = melt + warm

given: 15 g ice at 0 °C → liquid water at 50 °C · $\Delta H_{\text{fus}} = 335 \text{ J/g}$ · $c(\text{water}) = 4.184 \text{ J/g}\cdot^{\circ}\text{C}$

melt: $15 \text{ g} \times (\text{ — } \text{ J} / 1 \text{ g}) = \text{ — } \text{ J}$ · warm: $15 \text{ g} \times 4.184 \text{ J}/(\text{g}\cdot^{\circ}\text{C}) \times \text{ — } ^{\circ}\text{C} = 3138 \text{ J}$

Fill in ΔH_{fus} , the melt heat, and the temperature change, then add the two pieces.

melt: $15 \text{ g} \times (335 \text{ J} / 1 \text{ g}) = \mathbf{5025 \text{ J}}$ · warm: $15 \text{ g} \times 4.184 \text{ J}/(\text{g}\cdot^{\circ}\text{C}) \times 50 ^{\circ}\text{C} = \mathbf{3138 \text{ J}}$

total = $5025 \text{ J} + 3138 \text{ J} = \mathbf{8163 \text{ J}}$

 **Sense check:** The melt costs 5025 J, more than warming the liquid all the way to 50 °C. Melting is the larger step.



⚠ Where this goes wrong

reference: 30 g ice at 0 °C → liquid water at 25 °C

melt 10,050 J + warm 3138 J = 13,188 J · ΔH_{fus} 335 · $c(\text{ice})$ 2.03 · $c(\text{water})$ 4.184 J/g·°C

Treating a plateau as $q = m \cdot c \cdot \Delta T$. Multiplying the fusion heat by a ΔT , 45 g × 335 J/g × 40 °C = 603,000 J, invents heat. Melting holds at 0 °C, so 45 g × 335 J/g = 15,075 J, no ΔT .

Skipping the melting plateau. Warming the liquid only, 30 g × 4.184 J/g·°C × 25 °C = 3138 J, leaves the ice unmelted. Melting first costs another 10,050 J.

Stopping at the melting point. 30 g × 335 J/g = 10,050 J melts the ice but leaves it at 0 °C. Warming to 25 °C adds 3138 J.

Using the wrong phase's specific heat. Warming ice with water's 4.184, 20 g × 4.184 × 20 °C = 1673.6 J, overcharges it. Ice's c is 2.03: 20 g × 2.03 × 20 °C = 812 J.



Practice 2

total q = melt + warm

given: 20.0 g ice at 0 °C → liquid water at 30.0 °C · $\Delta H_{\text{fus}} = 335 \text{ J/g}$ · $c(\text{water}) = 4.184 \text{ J/g}\cdot^\circ\text{C}$ · wanted:
 q

A **20.0 g** block of ice at 0 °C is melted and warmed to 30.0 °C. How much heat, in J, does it take?

- A. 2.51×10^3
- B. 6.70×10^3
- C. 9.21×10^3
- D. 2.01×10^5

✓ Practice 2 answer: C

total q = melt + warm

given: 20.0 g ice at 0 °C → liquid water at 30.0 °C · $\Delta H_{\text{fus}} = 335 \text{ J/g}$ · $c(\text{water}) = 4.184 \text{ J/g}\cdot^{\circ}\text{C}$

$$\text{melt: } 20.0 \text{ g} \times (335 \text{ J} / 1 \text{ g}) = 6.70 \times 10^3 \text{ J} \cdot \text{warm: } 20.0 \text{ g} \times 4.184 \text{ J}/(\text{g} \cdot ^{\circ}\text{C}) \times 30.0 ^{\circ}\text{C} \\ = 2.51 \times 10^3 \text{ J}$$

$$q = 6.70 \times 10^3 \text{ J} + 2.51 \times 10^3 \text{ J} = \mathbf{9.21 \times 10^3 \text{ J} \cdot \text{answer C}}$$

A skipped the melting plateau: $20.0 \times 4.184 \times 30.0 = 2.51 \times 10^3 \text{ J}$ warms the liquid but never melts the ice. B stopped at the melting point: $20.0 \times 335 = 6.70 \times 10^3 \text{ J}$ leaves the water at 0 °C. D multiplied the plateau by a ΔT : $20.0 \times 335 \times 30.0 = 2.01 \times 10^5 \text{ J}$.

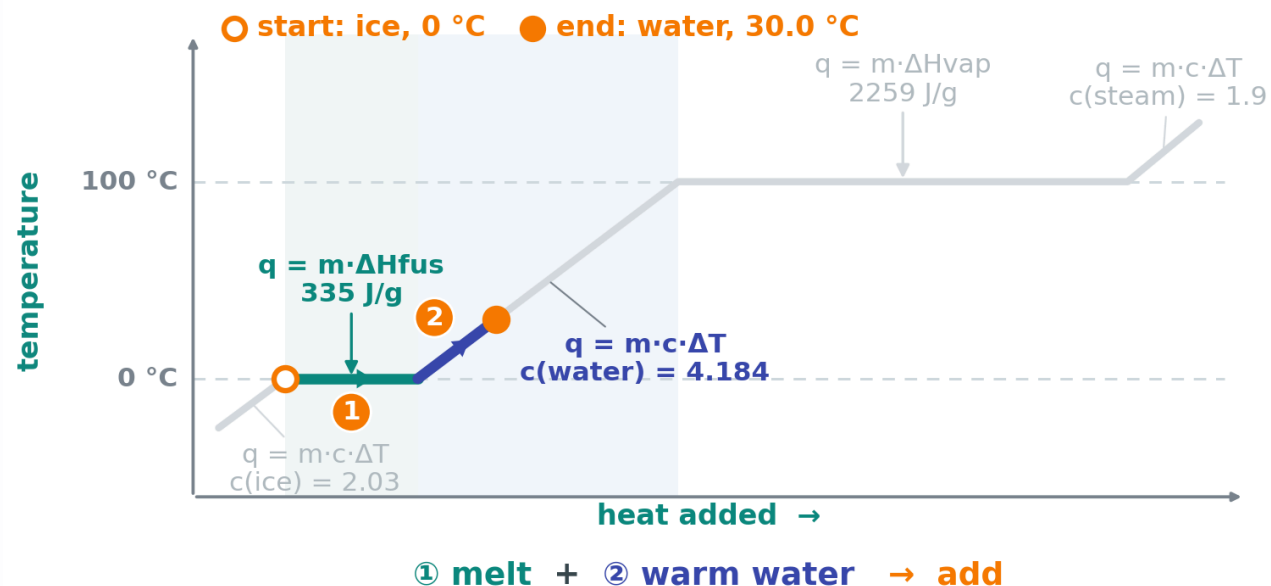


Sense check: Melting and warming are two separate costs, so both add ✓

✓ Practice 2: the route on the curve

total $q = \text{melt} + \text{warm}$

given: 20.0 g ice at 0 °C → liquid water at 30.0 °C · found: $q = 9.21 \times 10^3 \text{ J}$



🧠 **Sense check:** Two pieces: the melting plateau, then the water slope up to 30.0 °C. ✓

 Practice 3

total q = melt + warm

given: 72.1 g ice at 0 °C → liquid water at 20.0 °C · $\Delta H_{\text{fus}} = 6.02 \text{ kJ/mol}$ · $c(\text{water}) = 4.184 \text{ J/g} \cdot ^\circ\text{C}$ ·
18.02 g/mol · wanted: q in kJ

A cooler bag holds **72.1 g** of ice at 0 °C. What heat, in kJ, turns it into liquid water at **20.0 °C**?

- A. 4.40×10^2
- B. 30.1
- C. 24.1
- D. 6.06×10^3

✓ Practice 3 answer: B

total q = melt + warm

72.1 g ice, 0 °C → water, 20.0 °C · ΔH_{fus} 6.02 kJ/mol · c(water) 4.184 J/g·°C · 18.02 g/mol

$$\text{melt: } 72.1 \text{ g} \times \frac{1 \text{ mol}}{18.02 \text{ g}} \times \frac{6.02 \text{ kJ}}{1 \text{ mol}} = 24.1 \text{ kJ}$$

$$\text{warm: } 72.1 \times 4.184 \times 20.0 = 6033 \text{ J} = 6.03 \text{ kJ}$$

$$q = 24.1 \text{ kJ} + 6.03 \text{ kJ} = \mathbf{30.1 \text{ kJ} \cdot \text{answer B}}$$

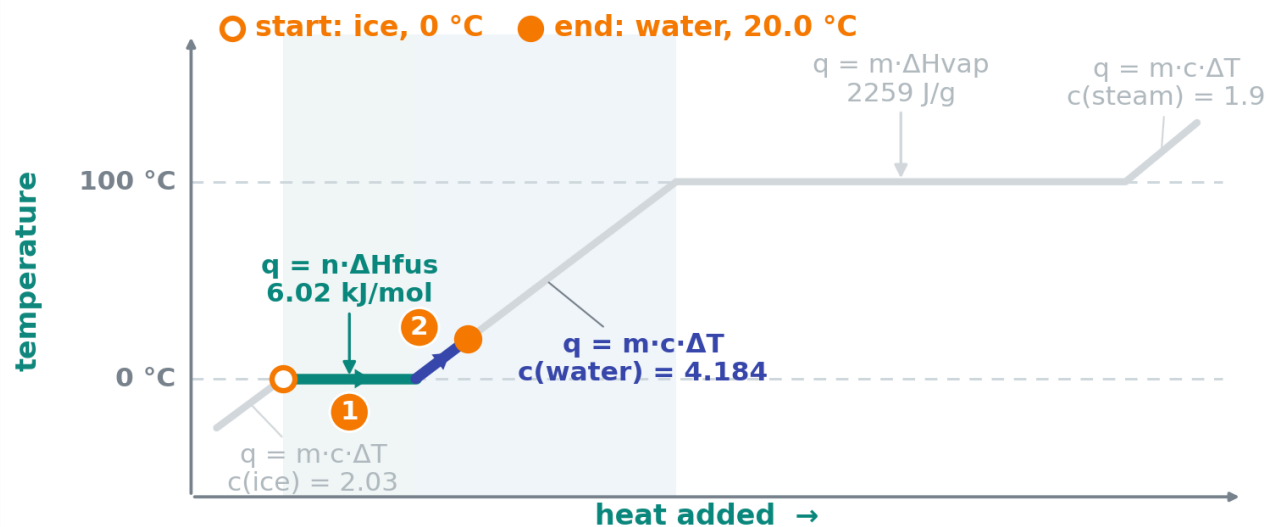
A used grams as moles: $72.1 \times 6.02 + 6.03 = 4.40 \times 10^2$. C stopped at the melting point: 24.1 kJ leaves the water at 0 °C. D added J to kJ as they stand: $24.1 + 6033 = 6.06 \times 10^3$.

🧠 **Sense check:** 72.1 g is 4.00 mol, so the melt is about 24 kJ. The warming adds a quarter more. ✓

✓ Practice 3: the route on the curve

total $q = \text{melt} + \text{warm}$

given: 72.1 g ice at 0 °C → liquid water at 20.0 °C · found: $q = 30.1 \text{ kJ}$



🧠 **Sense check:** The plateau per mole gives kJ, the slope gives J. One unit before adding. ✓



Practice 4

total q = cool steam + condense + cool water

given: 10.0 g steam at 115 °C $\rightarrow$ liquid water at 70.0 °C $\cdot c(\text{steam})$ 1.9 $\cdot c(\text{water})$ 4.184 J/g $\cdot$ °C $\cdot \Delta H_{\text{vap}}$
2259 J/g $\cdot$ wanted: q , signed

A **10.0 g** sample of steam at 115 °C cools, condenses, and ends as liquid water at 70.0 °C. What is q for the sample, in J?

- A. $+2.41 \times 10^4$
- B. -1.54×10^3
- C. -2.29×10^4
- D. -2.41×10^4

✓ Practice 4 answer: D

total q = cool steam + condense + cool water

given: $10.0 \text{ g} \cdot 115 \text{ }^{\circ}\text{C} \rightarrow 70.0 \text{ }^{\circ}\text{C} \cdot c(\text{steam}) 1.9 \cdot c(\text{water}) 4.184 \text{ J/g}\cdot^{\circ}\text{C} \cdot \Delta H_{\text{vap}} 2259 \text{ J/g} \cdot \Delta T = T_{\text{final}} - T_{\text{initial}}$

cool steam: $10.0 \text{ g} \times 1.9 \times (100 - 115) \text{ }^{\circ}\text{C} = -285 \text{ J} \cdot \text{condense: } -(10.0 \text{ g} \times 2259 \text{ J/g}) = -22,590 \text{ J} \cdot \text{cool water: } 10.0 \text{ g} \times 4.184 \times (70.0 - 100) \text{ }^{\circ}\text{C} = -1255 \text{ J}$

$q = -285 \text{ J} + (-22,590 \text{ J}) + (-1255 \text{ J}) = -24,130 \text{ J} = -2.41 \times 10^4 \text{ J} \cdot \text{answer D}$

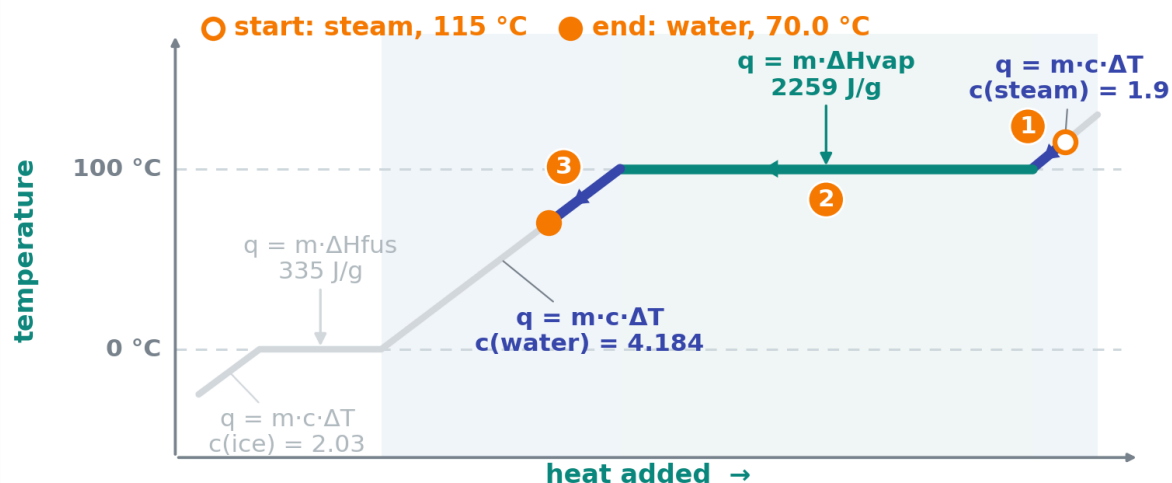
A lost the sign: a cooling path releases heat, so q is negative. B skipped the condensation plateau: $-285 - 1255 = -1.54 \times 10^3 \text{ J}$. C stopped at $100 \text{ }^{\circ}\text{C}$: $-285 - 22,590 = -2.29 \times 10^4 \text{ J}$.

🧠 **Sense check:** Heating curve run backward: every step is negative, condensing dominates ✓

✓ Practice 4: the route on the curve

total $q = \text{cool steam} + \text{condense} + \text{cool water}$

given: 10.0 g steam at 115 °C → liquid water at 70.0 °C · found: $q = -2.41 \times 10^4 \text{ J}$



① cool steam + ② condense + ③ cool water → every piece negative, add

🧠 **Sense check:** A cooling path runs the curve backward. Every piece releases heat: each q is negative. ✓



Practice 5

total q = the sum of every segment crossed

given: 27.0 g ice at $-12.0\text{ }^{\circ}\text{C}$ $\rightarrow$ liquid water at $35.0\text{ }^{\circ}\text{C}$ $\cdot c(\text{ice}) 2.03 \cdot c(\text{water}) 4.184\text{ J/g}\cdot^{\circ}\text{C} \cdot \Delta H_{\text{fus}} 6.02\text{ kJ/mol} \cdot 18.02\text{ g/mol}$ $\cdot$ wanted: q in J

A **27.0 g** ice cube at **$-12.0\text{ }^{\circ}\text{C}$** is heated until it is liquid water at **$35.0\text{ }^{\circ}\text{C}$** . What heat, in J, does it absorb?

- A. 1.30×10^4
- B. 4.61×10^3
- C. 1.43×10^4
- D. 9.68×10^3
- E. 1.36×10^4

✓ Practice 5 answer: E

given: 27.0 g ice, $-12.0\text{ }^{\circ}\text{C} \rightarrow$ water, $35.0\text{ }^{\circ}\text{C} \cdot c(\text{ice})\ 2.03 \cdot c(\text{water})\ 4.184\text{ J/g}\cdot^{\circ}\text{C} \cdot \Delta H_{\text{fus}}\ 6.02\text{ kJ/mol} \cdot 18.02\text{ g/mol}$

warm ice: $27.0 \times 2.03 \times 12.0 = 658\text{ J}$ · warm water: $27.0 \times 4.184 \times 35.0 = 3954\text{ J}$

$$\text{melt: } 27.0\text{ g} \times \frac{1\text{ mol}}{18.02\text{ g}} \times \frac{6.02\text{ kJ}}{1\text{ mol}} = 9020\text{ J} \cdot q = 658 + 9020 + 3954$$

$= 1.36 \times 10^4\text{ J} \cdot \text{answer E}$

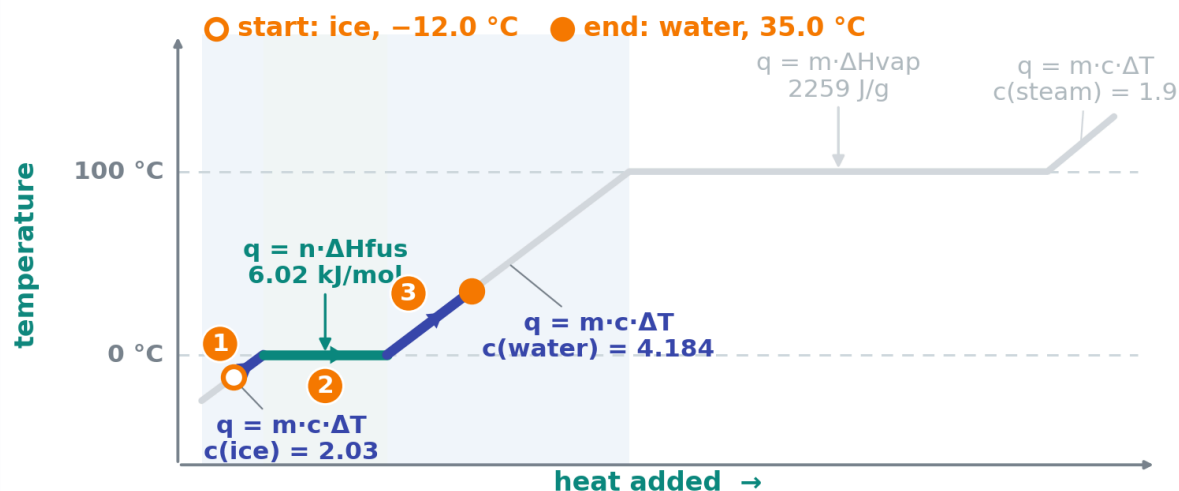
A skipped the ice leg: $9020 + 3954 = 1.30 \times 10^4$. B skipped the melt: $658 + 3954 = 4.61 \times 10^3$. C used $c(\text{water})$ on ice: $1356 + 9020 + 3954 = 1.43 \times 10^4$. D stopped at $0\text{ }^{\circ}\text{C}$: $658 + 9020 = 9.68 \times 10^3$.

 **Sense check:** The melt, $9.02\text{ kJ} = 9020\text{ J}$, is two-thirds of the total. ✓

✓ Practice 5: the route on the curve

total q = warm ice + melt + warm water

given: 27.0 g ice at $-12.0\text{ }^{\circ}\text{C}$ → liquid water at $35.0\text{ }^{\circ}\text{C}$ · found: $q = 1.36 \times 10^4\text{ J}$



① warm ice + ② melt + ③ warm water → kJ and J to one unit, then add

🧠 **Sense check:** Two slopes and the per-mole plateau between them. Its kJ became J before the sum. ✓

 Practice 6

total q = cool water + freeze

given: 50.0 g liquid water at 22.0 °C → ice at 0 °C · $c(\text{water})$ 4.184 · $c(\text{ice})$ 2.03 J/g·°C · ΔH_{fus} 335 J/g ·
wanted: q , signed

A bottle holding **50.0 g** of water at **22.0 °C** goes into a freezer and ends as ice at 0 °C.
What is q for the water, in J?

- A. -1.68×10^4
- B. $+2.14 \times 10^4$
- C. -4.60×10^3
- D. -2.14×10^4
- E. -1.90×10^4

✓ Practice 6 answer: D

total q = cool water + freeze

given: 50.0 g · 22.0 °C → ice at 0 °C · c(water) 4.184 J/g·°C · ΔH_{fus} 335 J/g · ΔT = T_{final} – T_{initial}

cool water: 50.0 g × 4.184 J/(g·°C) × (0 – 22.0) °C = –4602 J

freeze: –(50.0 g × 335 J/g) = –16,750 J

$q = -4602 \text{ J} + (-16,750 \text{ J}) = -21,352 \text{ J} = \mathbf{-2.14 \times 10^4 \text{ J} \cdot \text{answer D}}$

A skipped the cooling leg: $-16,750 \text{ J} = -1.68 \times 10^4 \text{ J}$. B lost the sign: the water releases heat, so q is negative. C skipped the freezing plateau: $-4.60 \times 10^3 \text{ J}$. E cooled the liquid with ice's c: $50.0 \times 2.03 \times (-22.0) - 16,750 = -1.90 \times 10^4 \text{ J}$.

 **Sense check:** Freezing releases more than three times the heat of the cooling. ✓



Practice 7

total q = the sum of every segment crossed

given: 54.0 g water at 65.0 °C → steam at 140.0 °C · $c(\text{water})$ 4.184 · $c(\text{steam})$ 1.9 J/g·°C · ΔH_{vap} 40.7 kJ/mol · 18.02 g/mol · wanted: q in kJ

A pot holds **54.0 g** of water at **65.0 °C**. It is heated until all of it is steam at **140.0 °C**. How much heat, in kJ, does that take?

- A. 130.
- B. 144
- C. 134
- D. 1.21×10^4

✓ Practice 7 answer: C

54.0 g water, 65.0 °C → steam, 140.0 °C · c(water) 4.184 · c(steam) 1.9 J/g·°C · ΔHvap 40.7 kJ/mol

warm water: $54.0 \times 4.184 \times 35.0 = 7908 \text{ J} = 7.91 \text{ kJ}$

warm steam: $54.0 \times 1.9 \times 40.0 = 4104 \text{ J} = 4.10 \text{ kJ}$

$$\text{boil: } 54.0 \text{ g} \times \frac{1 \text{ mol}}{18.02 \text{ g}} \times \frac{40.7 \text{ kJ}}{1 \text{ mol}} = 122 \text{ kJ} \cdot q = 7.91 + 122 + 4.10$$

= 134 kJ · answer C

A stopped at 100 °C: $7.91 + 122 = 130$. B used 140.0 °C as the steam's ΔT: $54.0 \times 1.9 \times 140.0 = 14.4 \text{ kJ}$, total 144. D added J to kJ as they stand: $7908 + 122 + 4104 = 1.21 \times 10^4$.

🧠 **Sense check:** 54.0 g is 3.00 mol. Boiling is 122 kJ; the slopes add 12.0 kJ. ✓



Check yourself

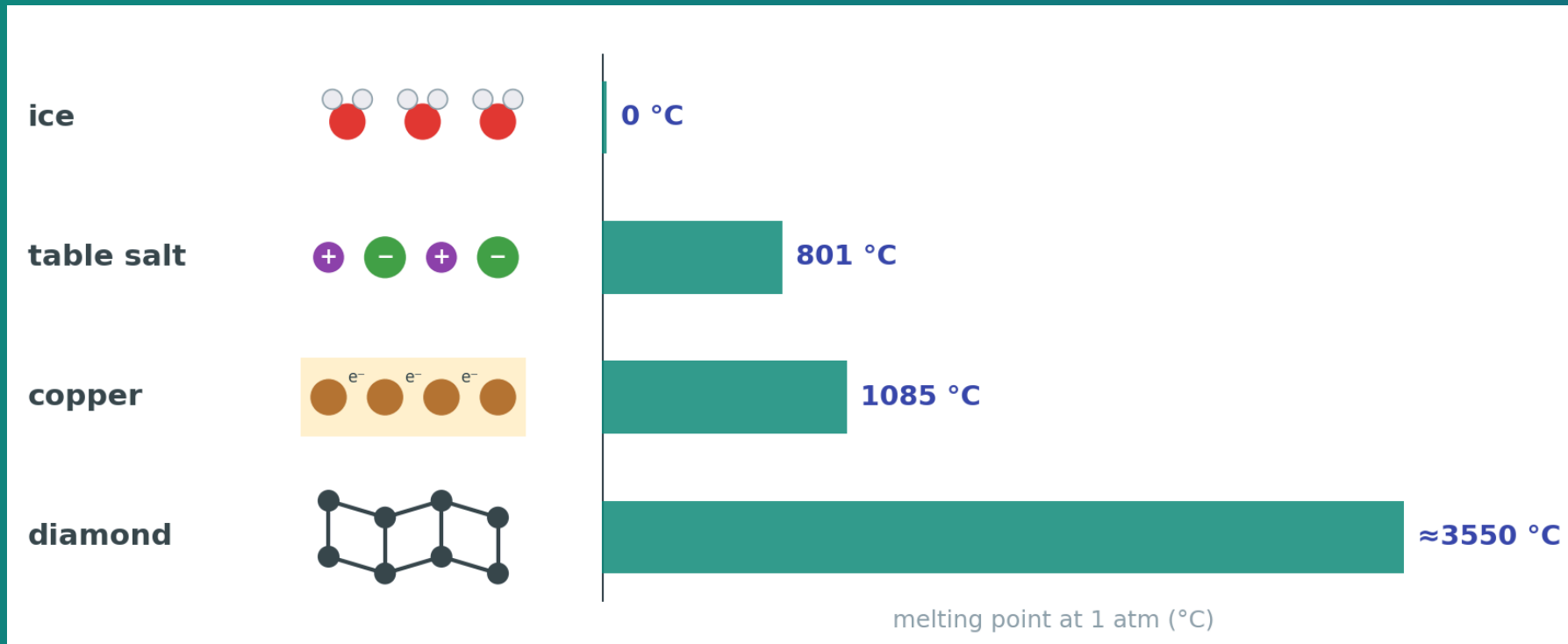
1. A path crosses a flat plateau, then a rising slope. Which equation does each part use?
Why does the plateau carry no ΔT ?
2. Water at 100 °C and steam at 100 °C are the same temperature. Why does boiling the water still take heat?

The plateaus are long because melting and boiling pull particles apart. How hard the particles hold on differs from solid to solid: ionic, metallic, molecular, and network solids melt at very different temperatures.

7 • 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.

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

What holds a solid together

A solid holds its particles in fixed positions. A force keeps them there, and melting must overcome it. That force is one of the three intermolecular forces or one of three kinds of bond.

between separate molecules: intermolecular forces

dispersion · dipole-dipole · hydrogen bonding · weak: a molecular solid melts low

through the whole crystal: bonds

ionic bonds · metallic bonding · covalent bonds · ionic and network solids melt high · metals vary

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

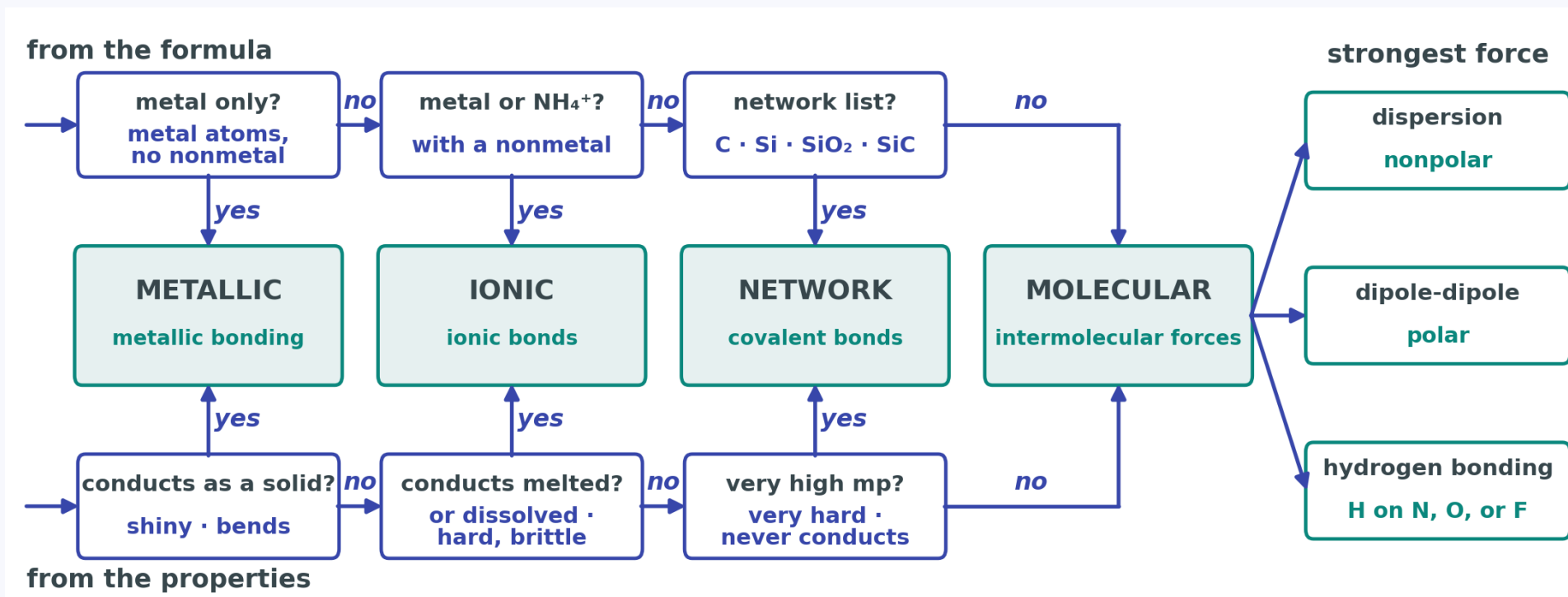
Melting point tracks the holding force: covalent network ≥ ionic > metallic > molecular

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.





Guided example: hydrogen chloride

HCl(s): hydrogen chloride, frozen

given: the formula HCl · wanted: the solid type, its strongest force, its properties

Hydrogen chloride is a gas at room temperature. Cooled far enough, it freezes into a crystal. Classify solid HCl, then predict its properties.

Step 1 asks the formula questions in order: metal only? A metal or NH_4^+ with a nonmetal? On the network list?

✓ Guided example: name the particle

HCl(s): hydrogen chloride, frozen

given: the formula HCl · wanted: type, strongest force, properties

Step 1 · Name the particle

move 1 · metal only? no

H sits above the group 1 metals, but hydrogen is a nonmetal

move 2 · a metal or NH_4^+ with a nonmetal? no

no metal, no NH_4^+ · H and Cl share electrons: no ions

move 3 · on the network list? no

not C, Si, SiO_2 , or SiC · particle: the HCl molecule → a molecular solid

🧠 **Sense check:** Three no answers leave one type. Each HCl unit is a separate molecule. ✓

✓ Guided example: force and properties

HCl(s): a molecular solid

particle: HCl molecules · wanted: strongest force, properties

Step 2 · Name the force

polar molecule · H bonded to Cl, not to N, O, or F → **dipole-dipole**, plus dispersion

Step 3 · Predict the properties

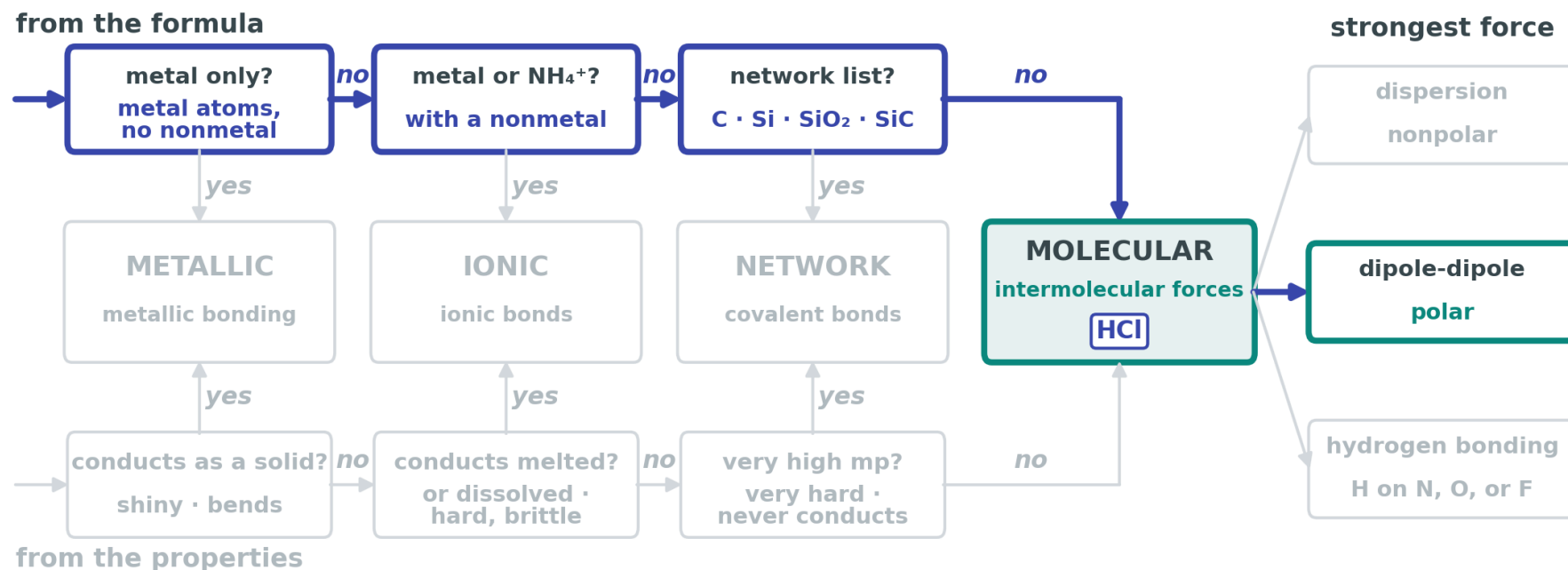
intermolecular forces only → **low melting point · soft · nonconducting**

🧠 **Sense check:** Solid HCl melts at $-114\text{ }^{\circ}\text{C}$, $114\text{ }^{\circ}\text{C}$ below ice. Its molecules carry no net charge, so the solid does not conduct. ✓

✓ Guided example: the route on the map

HCl(s): molecular solid · dipole-dipole

metal only? no · metal or NH_4^+ ? no · network list? no · polar, no H on N, O, or F



 **Sense check:** The formula row alone found the type. No melting point or conductivity test was needed. ✓



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 →

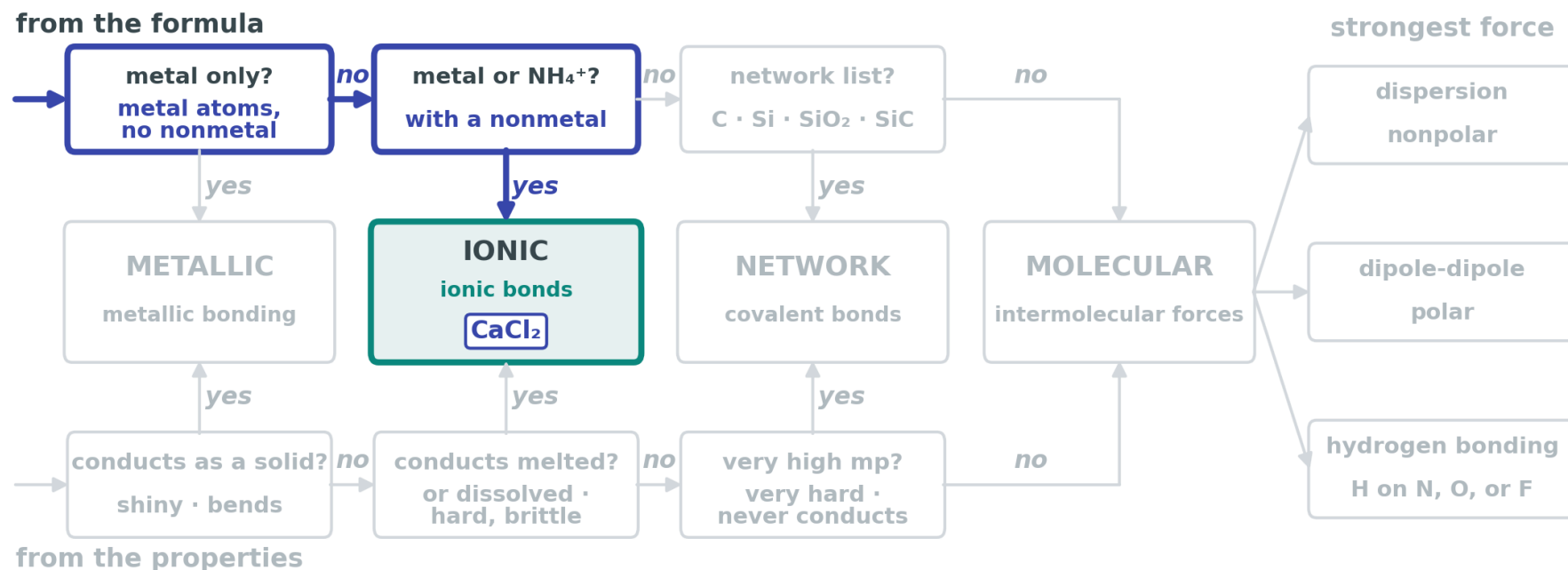
high melting point · hard but brittle · conducts only when molten or dissolved

 **Sense check:** CaCl_2 melts at 772°C , near table salt's 801°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**

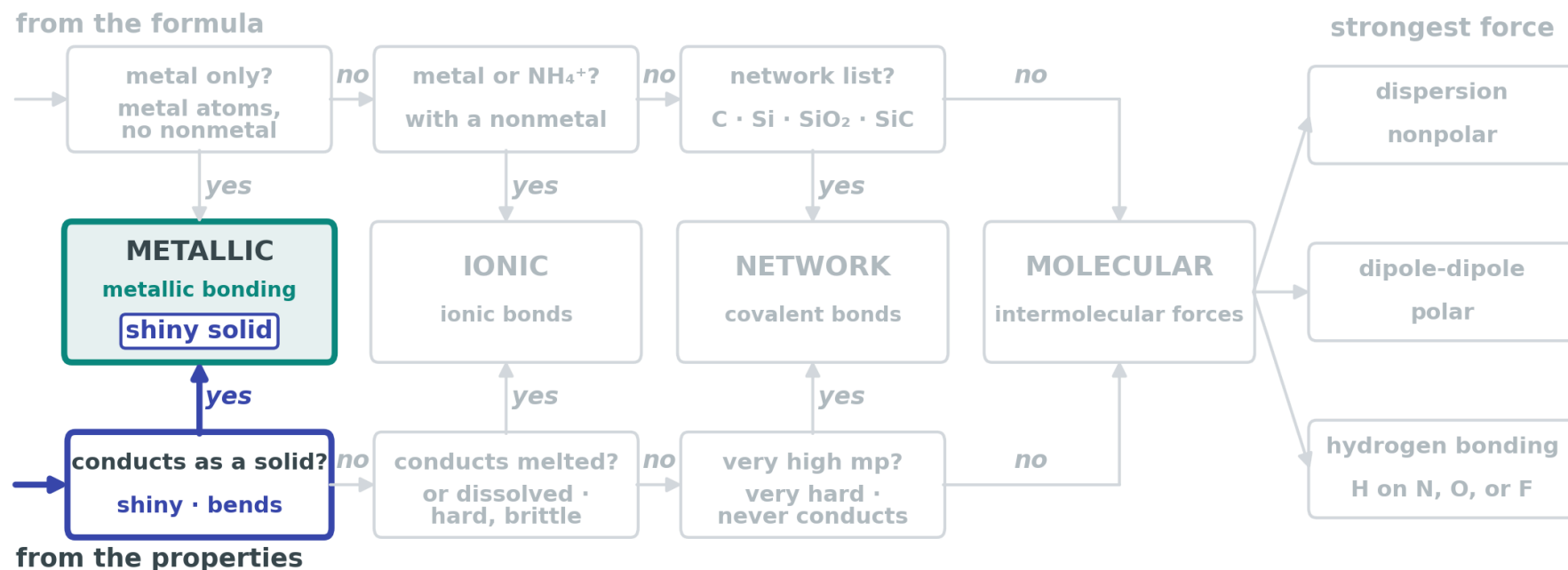
Step 3 · Predict the properties

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



nickel · nickel(II) oxide · silicon · sulfur

Which of these forms a metallic solid?

- A. Ni
- B. NiO
- C. Si
- D. S₈

✓ Practice 1 answer: A

Ni: metal atoms only → **metallic solid**, answer A

B contains a metal, but Ni with O is a metal with a nonmetal: ionic. C is shiny and gray, but silicon is on the network list: a covalent network. D is a single element, but sulfur is a nonmetal: S₈ molecules make a molecular solid.

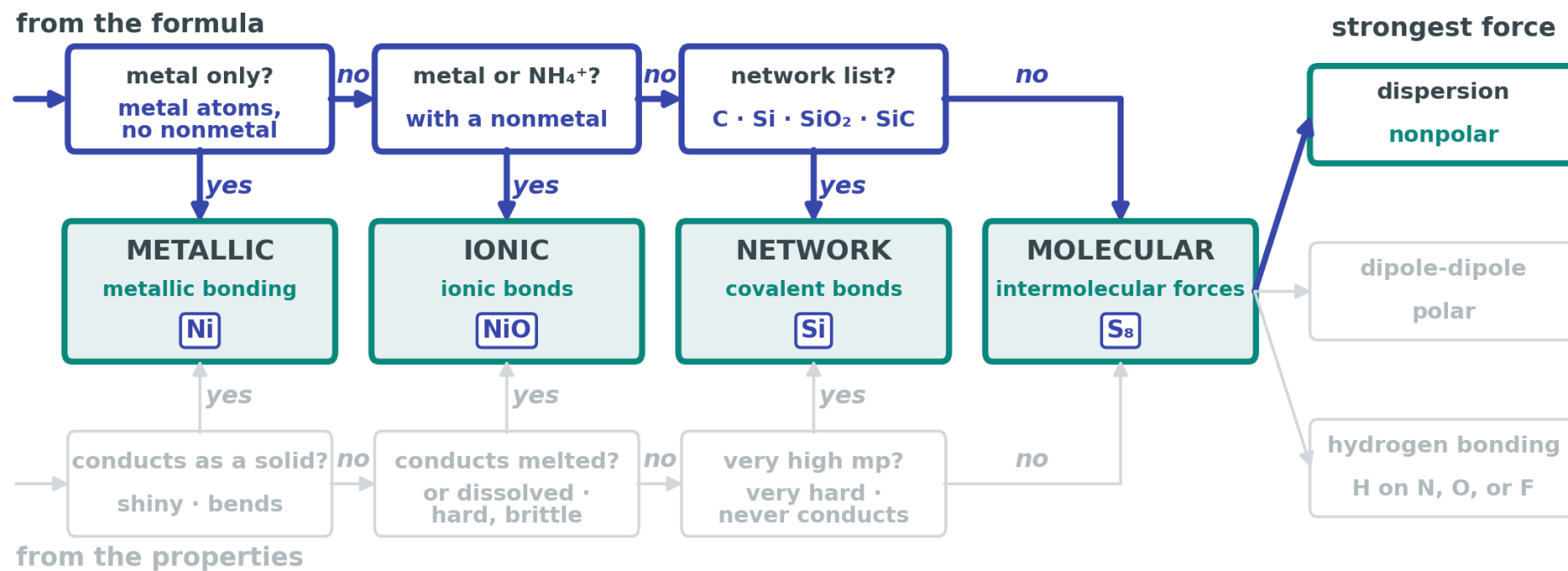
🧠 **Sense check:** A metallic solid holds metal atoms and nothing else. Nickel is the only choice with no nonmetal in it.



✓ Practice 1: the route on the map

Ni · NiO · Si · S₈

Ni: metal only · NiO: metal with O · Si: network list · S₈: molecules, nonpolar



🧠 **Sense check:** Four formulas leave by four exits. Only Ni stops at the first question. ✓



Practice 2

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 2 answer: C

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

→ **covalent network**, answer C

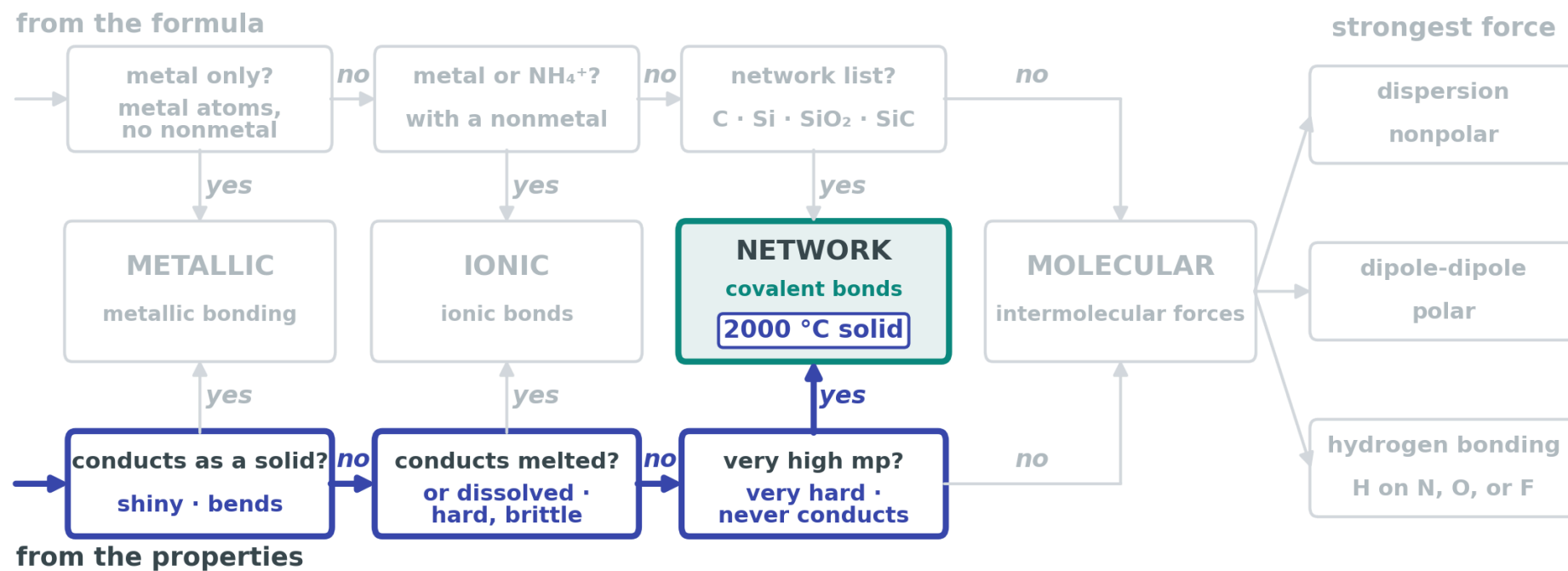
A matched hardness and melting point but skipped the molten test: a melted ionic solid conducts. B ignored the conductivity; a metal conducts as a solid. D read only the conductivity; a molecular solid melts low and is soft, never near 2000 °C.

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

✓ Practice 2: the route on the map

the colorless solid: covalent network

conducts as a solid? no · melted? no · very hard, very high mp? yes



 **Sense check:** No formula was given, so the property row did the sorting. Three questions were needed. ✓



Practice 3

ammonium nitrate, NH_4NO_3 : a fertilizer
a white crystalline solid · wanted: the solid type and when it conducts

Which type of solid is ammonium nitrate, and when does it conduct?

- A. Molecular: only nonmetals, so it never conducts
- B. Ionic: conducts once melted or dissolved
- C. Covalent network: nonmetal atoms bonded throughout one crystal
- D. Ionic: conducts as a solid

✓ Practice 3 answer: B

NH_4^+ and NO_3^- ions $\rightarrow$ ionic bonds

$\rightarrow$ **ionic solid**, conducts once melted or dissolved, answer B

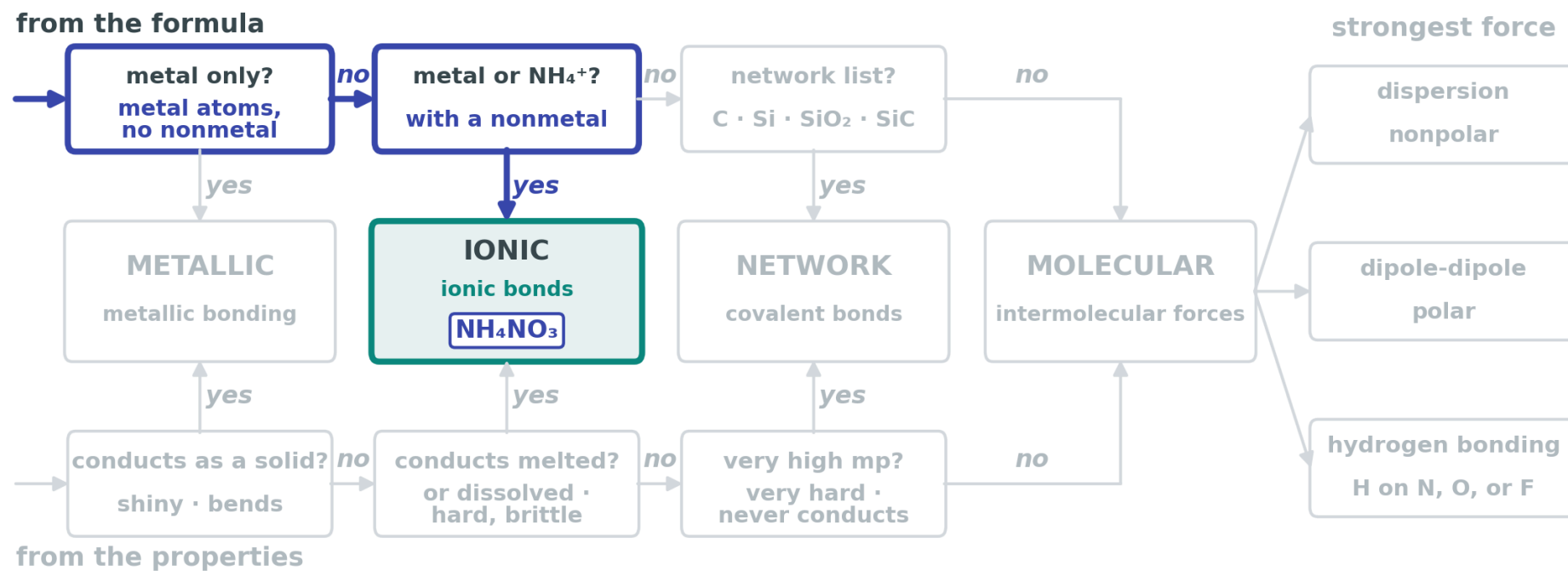
A applied the nonmetals-only rule without looking for a polyatomic ion. NH_4^+ and NO_3^- carry charges, so the solid is built of ions. C picked a network solid, but the network list is short: C, Si, SiO_2 , SiC. D named the right type but let the ions move in the solid; in the lattice they are locked in place.

🧠 **Sense check:** Ammonium nitrate is a salt like NaCl. Dissolved in soil water, its ions move freely, and the solution conducts. ✓

✓ Practice 3: the route on the map

NH_4NO_3 : an ionic solid

metal only? no · a metal or NH_4^+ with a nonmetal? yes, NH_4^+ with NO_3^-



🧠 **Sense check:** NH_4^+ answers the second question just as a metal would. ✓



Practice 4

urea, $\text{CO}(\text{NH}_2)_2$: a crystalline fertilizer
melts at 133 °C

What type of solid is urea, and what is the strongest force between its particles?

- A. Ionic · ionic bonds
- B. Covalent network · covalent bonds
- C. Molecular · dispersion
- D. Molecular · dipole-dipole
- E. Molecular · hydrogen bonding

✓ Practice 4 answer: E

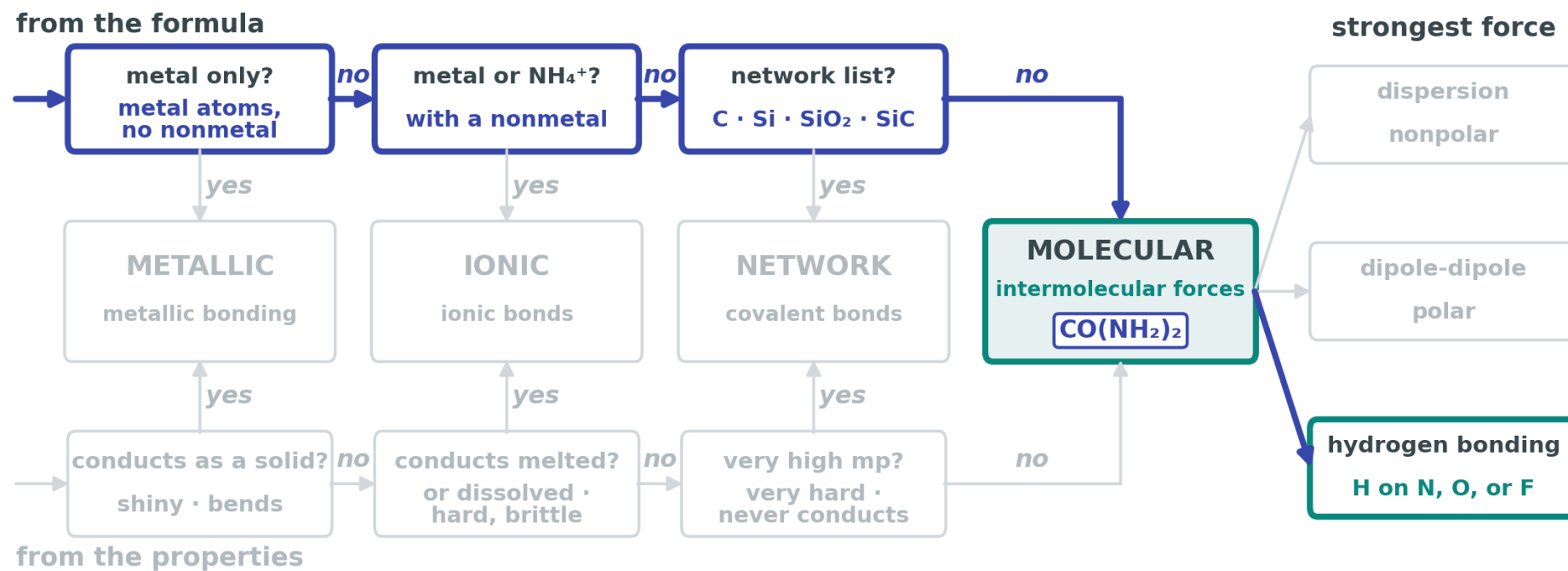
nonmetals only · no NH_4^+ · not on the network list → molecules · H bonded to N
→ **molecular, hydrogen bonding**, answer E

A read each NH_2 group as ammonium. NH_4^+ carries 4 H and a charge; urea holds $2 \times 2 = 4$ H in two neutral NH_2 groups and no ion. B named the covalent bonds inside each molecule; melting separates whole molecules and breaks none of those bonds. C stopped at dispersion, the force every molecule has. D saw a polar molecule but missed H bonded to N.

 **Sense check:** No network solid melts near 133 °C. The heat separates whole urea molecules held by N-H hydrogen bonds. ✓

✓ Practice 4: the route on the map

CO(NH₂)₂: molecular · hydrogen bonding
 metal only? no · metal or NH₄⁺? no · network list? no · H bonded to N



 **Sense check:** Three no answers reach molecular; the H on N picks the strongest force. ✓



Practice 5

an unlabeled stockroom solid

soft enough to cut with a knife · melts at 98 °C · conducts electricity as a solid

What type of solid is it?

- A. Ionic
- B. Molecular (nonpolar)
- C. Molecular (polar)
- D. Metallic
- E. Covalent network

✓ Practice 5 answer: D

conducts as a solid? yes → **metallic**, answer D

Conductivity decides first. Softness and a 98 °C melting point fit a metal too: metallic melting points vary widely.

A let the ions move in the solid; an ionic solid conducts only once melted or dissolved. B let the softness and the low melting point outvote the conductivity. C read polarity as charge; polar molecules carry no net charge and never conduct. E reached for graphite, the one conducting network; graphite stays solid past 3500 °C.

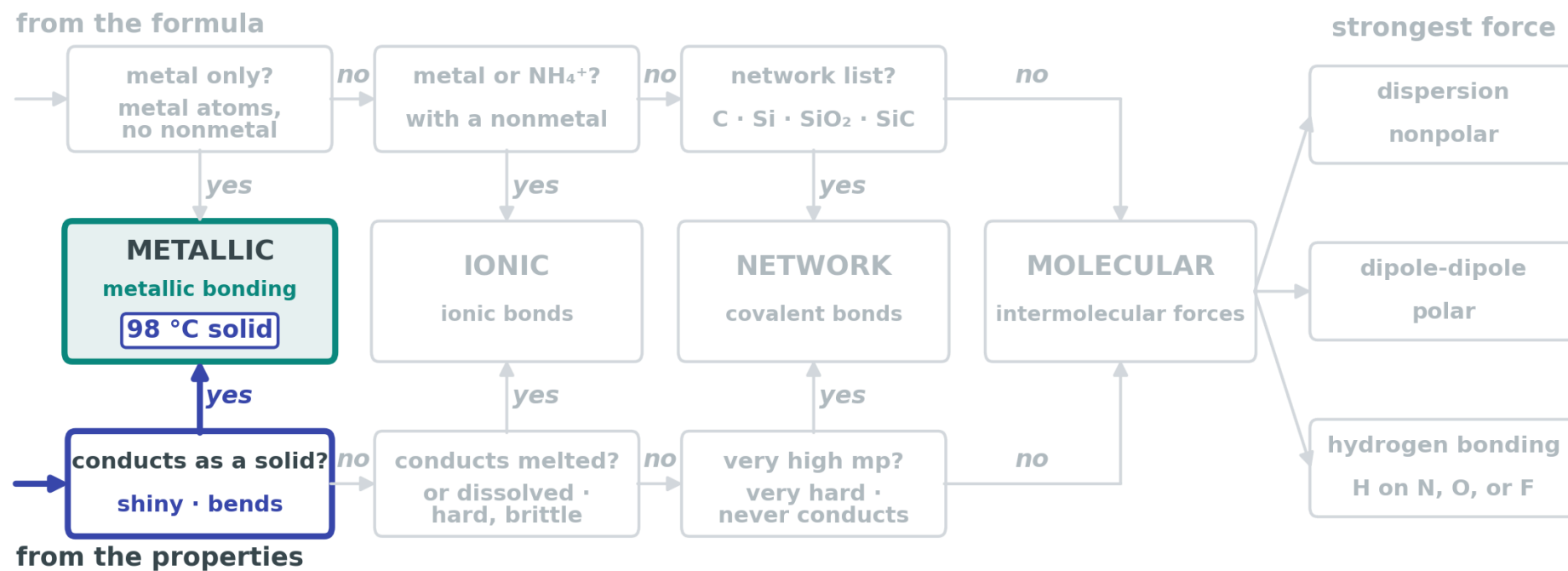


Sense check: This is sodium: soft, melting at 98 °C, conducting like any metal. ✓

✓ Practice 5: the route on the map

the 98 °C solid: metallic

conducts as a solid? yes · softness and melting point never enter the route



 **Sense check:** The first property question settles it. Softness and a low melting point do not rule out a metal. ✓



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. ✓



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...?

- ☐ name the six changes of state, label each endothermic or exothermic, and read a heating or cooling curve?
- ☐ calculate the heat for warming steps with $q = mc\Delta T$ and for phase changes with the heats of fusion and vaporization, and add them along a heating curve?
- ☐ identify the intermolecular forces in a substance and rank substances by boiling point and vapor pressure?
- ☐ explain vapor pressure, boiling point, surface tension, and viscosity from intermolecular forces, including why boiling point changes with outside pressure?
- ☐ read a phase diagram: the stable phase at a given pressure and temperature, the triple point, and the normal melting and boiling points?
- ☐ classify a solid as ionic, metallic, molecular, or network and predict its melting point, hardness, and conductivity?

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