

Substance Experts: Why Each Substance Changes State at Its Own Temperature

Learning target: I can work with my group to compare the melting and boiling points of twelve pure substances, predict each one's state at a given temperature, and explain the pattern with how strongly their particles attract one another.

Collaborative investigation

About 50 min

Jigsaw

MS-PS1-4 · practice

collaboration

discussion

data analysis

Standards connections

MS-PS1-4 (practice, predicting the state of a pure substance at a given temperature from how strongly its particles attract): Groups use melting and boiling points to predict the state of twelve pure substances, including the examples the clarification statement names (water, carbon dioxide, helium), and explain the pattern with particle attractions. This practices the predictive side of the PE; the individual section checks each student's reasoning.

Purpose: practice · **Time:** about 50 minutes · **Format:** jigsaw

Answers with reasoning

Twelve substance cards (cut apart; all values at normal air pressure)

1 Card 1: Helium

Boils at about -269°C at normal air pressure. It cannot be frozen at all at normal air pressure, no matter how cold it gets; it becomes solid only when it is also squeezed under high pressure. Liquid helium keeps the magnets inside hospital MRI scanners extremely cold. Expert group A.

2 Card 2: Nitrogen

Melts at about -210°C and boils at about -196°C at normal air pressure. About 78 percent of the air you breathe is nitrogen gas. Liquid nitrogen is used to freeze foods quickly and to store cell samples. Expert group A.

3 Card 3: Oxygen

Melts at about -219°C and boils at about -183°C at normal air pressure. About 21 percent of the air is oxygen. Hospitals often store oxygen as a liquid in insulated tanks, because the liquid takes up far less space than the same amount of gas. Expert group A.

4 Card 4: Methane

Melts at about -182°C and boils at about -162°C at normal air pressure. Methane is the main part of natural gas. Its molecules have about the same mass as water molecules, yet it is a gas at room temperature. Ships carry it across oceans as a liquid chilled below -162°C . Expert group B.

5 Card 5: Carbon dioxide

At normal air pressure it has no liquid state at all. Solid carbon dioxide, called dry ice, sublimates straight into gas at about -78°C . Liquid carbon dioxide can exist only when it is squeezed to more than about five times normal air pressure, as inside a fire extinguisher. Expert group B.

6 Card 6: Ethanol

Melts at about -114°C and boils at about 78°C at normal air pressure. Ethanol is the alcohol in many hand sanitizers. It evaporates from your skin within seconds, which is why sanitizer feels cool. Expert group B.

7 Card 7: Water

Melts at 0°C and boils at 100°C at normal (sea-level) air pressure. Water molecules are small and light, but they attract one another unusually strongly for their size. That is why water is a liquid at room temperature while methane, made of molecules of about the same mass, is a gas. Expert group C.

8 Card 8: Mercury

Melts at about -39°C and boils at about 357°C at normal air pressure. It is the only common metal that is a liquid at room temperature. Its vapor is poisonous, so schools have replaced mercury thermometers with digital or alcohol ones. Expert group C.

9 Card 9: Table salt (sodium chloride)

Melts at about 801°C and boils at about $1,465^{\circ}\text{C}$ at normal air pressure. Salt is made of particles with opposite electric charges that pull on one another very strongly. Expert group C.

10 Card 10: Aluminum

Melts at about 660°C and boils at about $2,470^{\circ}\text{C}$ at normal air pressure. Recycled cans are melted in furnaces; the liquid metal is poured into molds and freezes into solid blocks at about 660°C , long before it cools to room temperature. Expert group D.

11 Card 11: Copper

Melts at about $1,085^{\circ}\text{C}$ and boils at about $2,560^{\circ}\text{C}$ at normal air pressure. Copper is used for electrical wires, water pipes and the bottoms of some cooking pots. Expert group D.

12 Card 12: Iron

Melts at about $1,538^{\circ}\text{C}$ and boils at about $2,860^{\circ}\text{C}$ at normal air pressure. Steel, which is mostly iron, is melted in huge furnaces and poured into molds. Of the twelve substances on these cards, iron has the highest boiling point. Expert group D.

Part A: Expert round

1. Record your expert group's three substances. If a substance has no liquid state or no melting point at normal pressure, write that and explain it to your group.

Answer: Group A: helium (no melting point at normal pressure, bp about -269 , gas), nitrogen (-210 , -196 , gas), oxygen (-219 , -183 , gas). Group B: methane (-182 , -162 , gas), carbon dioxide (no liquid at normal pressure; sublimates at about -78 , gas), ethanol (-114 , 78 , liquid). Group C: water (0 , 100 , liquid), mercury (-39 , 357 , liquid), table salt (801 , $1,465$, solid). Group D: aluminum (660 , $2,470$, solid), copper ($1,085$, $2,560$, solid), iron ($1,538$, $2,860$, solid).

Why: Values come straight from the cards; the state at 25°C follows from where 25°C falls between the melting and boiling points.

Also acceptable: Any accurate fact from the card is acceptable in the last column.

- Values copied accurately
- State at 25°C correct for all three substances
- Special cases for helium and carbon dioxide explained

Part B: Home group task

1. Each expert reads their three cards aloud and teaches the group the most surprising fact.
 2. Lay all twelve cards in a column from the lowest boiling point at the bottom to the highest at the top. Place carbon dioxide by the temperature at which it sublimates, and mark it with a star.
 3. Lay a paper strip beside the column and mark three lines on it: $-100\text{ }^{\circ}\text{C}$, $25\text{ }^{\circ}\text{C}$ (room temperature) and $200\text{ }^{\circ}\text{C}$.
 4. For each line, decide which substances would be solid, liquid or gas at that temperature, and complete the group record.
 5. Agree on an answer to each question in Part B before anyone writes it down.
2. Group record: write S (solid), L (liquid) or G (gas) for each substance at each temperature, at normal air pressure.

Answer: At $-100\text{ }^{\circ}\text{C}$: helium G, nitrogen G, oxygen G, methane G, carbon dioxide S, ethanol L, water S, mercury S, salt S, aluminum S, copper S, iron S. At $25\text{ }^{\circ}\text{C}$: helium G, nitrogen G, oxygen G, methane G, carbon dioxide G, ethanol L, water L, mercury L, salt S, aluminum S, copper S, iron S. At $200\text{ }^{\circ}\text{C}$: helium G, nitrogen G, oxygen G, methane G, carbon dioxide G, ethanol G, water G, mercury L, salt S, aluminum S, copper S, iron S.

Why: Below the melting point a substance is solid, between the two points it is liquid, above the boiling point it is gas. Carbon dioxide is solid below $-78\text{ }^{\circ}\text{C}$ and gas above it. Ethanol is liquid at $-100\text{ }^{\circ}\text{C}$ because its melting point is $-114\text{ }^{\circ}\text{C}$; mercury is still liquid at $200\text{ }^{\circ}\text{C}$ because it boils at $357\text{ }^{\circ}\text{C}$.

Also acceptable: None; the values decide each cell.

- At least 34 of 36 cells correct
- Carbon dioxide solid at $-100\text{ }^{\circ}\text{C}$ and gas at $25\text{ }^{\circ}\text{C}$
- Ethanol liquid at $-100\text{ }^{\circ}\text{C}$; mercury liquid at $200\text{ }^{\circ}\text{C}$

3. Write your boiling-point ladder from lowest to highest. Then use it to rank the substances from the weakest to the strongest attractions between particles, and explain why a boiling point can be used this way.

Answer: Ladder (lowest to highest): helium (-269), nitrogen (-196), oxygen (-183), methane (-162), carbon dioxide (-78 , sublimates, starred), ethanol (78), water (100), mercury (357), table salt ($1,465$), aluminum ($2,470$), copper ($2,560$), iron ($2,860$). Weakest to strongest attractions follows the same order. Boiling separates particles completely from one another, so the more strongly they attract, the more energy they need and the higher the temperature at which this happens.

Why: The lesson links boiling and melting points to attraction strength; the boiling point is the cleaner guide because boiling pulls particles fully apart.

Also acceptable: Accept carbon dioxide placed by sublimation and noted as a special case in any wording.

- Ladder in correct order with carbon dioxide marked
- Attraction ranking matches the ladder
- Explains that stronger attractions need more energy, so a higher boiling point

4. Now order the substances by melting point instead. Find at least one pair of substances whose order swaps between the two ladders. What might explain the swap?

Answer: Melting-point order (lowest to highest): oxygen (−219), nitrogen (−210), methane (−182), ethanol (−114), mercury (−39), water (0), aluminum (660), salt (801), copper (1,085), iron (1,538); helium has none and carbon dioxide does not melt at normal pressure. Swaps include nitrogen and oxygen (oxygen melts lower but boils higher), water and mercury (water melts higher but boils lower), and salt and aluminum (salt melts higher but boils lower). Melting only loosens particles from a fixed pattern, so it also depends on how neatly the particles fit together in the solid; boiling pulls them completely apart, so it is a better guide to attraction strength.

Why: This is a deliberate limit of the simple model: attraction strength explains the broad pattern, but melting points also depend on how the solid is built.

Also acceptable: Accept 'the model is not perfect; melting and boiling measure slightly different things' as the explanation.

- Names at least one real swap
- Offers a reasonable explanation (melting also depends on how particles are arranged in the solid, or the attraction model is a simplification)

5. Imagine a furnace at 1,000 °C. Which of these four substances would be liquid in it: table salt, aluminum, copper and iron, and which would still be solid? Show how you decided.

Answer: Liquid at 1,000 °C: table salt (melts at 801 °C, boils at 1,465 °C) and aluminum (melts at 660 °C, boils at 2,470 °C). Still solid: copper (melts at 1,085 °C) and iron (melts at 1,538 °C). For each, compare 1,000 °C with the melting point: above it and below the boiling point means liquid; below the melting point means solid.

Why: 1,000 °C lies above the melting points of salt and aluminum but below those of copper and iron.

Also acceptable: None.

- Salt and aluminum liquid
- Copper and iron solid
- Method stated

Part C: Individual accountability (complete alone)

6. Substance X, an ingredient in some nail-polish removers, melts at about −95 °C and boils at about 56 °C. What state is it in at 25 °C? Where would it go on your ladder? Are its particles more or less strongly attracted to one another than water's? Explain.

Answer: Liquid at 25 °C, because 25 °C is between −95 °C and 56 °C. On the boiling-point ladder it goes between carbon dioxide (−78) and ethanol (78). Its particles are less strongly attracted than water's, because it boils at a lower temperature (56 °C versus 100 °C), so less energy is needed to pull them apart.

Why: The substance is acetone; students do not need the name. Its position follows from its boiling point.

Also acceptable: Accept 'just below ethanol' for the position.

- Liquid at 25 °C with reason
- Correct ladder position
- Weaker attractions than water, explained with the lower boiling point

7. Two tanks, one of pure nitrogen gas and one of pure oxygen gas, are slowly cooled to $-190\text{ }^{\circ}\text{C}$ while each is kept at normal air pressure. Will either tank now contain liquid? If so, which gas condensed, and which one is still a gas? Use the cards to explain.

Answer: Yes, the oxygen tank. Oxygen boils at about $-183\text{ }^{\circ}\text{C}$, so at $-190\text{ }^{\circ}\text{C}$, below its boiling point, it has condensed into a liquid (it would freeze only at about $-219\text{ }^{\circ}\text{C}$). Nitrogen boils at about $-196\text{ }^{\circ}\text{C}$, so at $-190\text{ }^{\circ}\text{C}$ it is still above its boiling point and stays a gas.

Why: $-190\text{ }^{\circ}\text{C}$ lies below oxygen's boiling point but above nitrogen's. The item uses two pure gases on purpose: in air the oxygen is mixed with nitrogen, and air at normal pressure does not start to liquefy until a little below $-191\text{ }^{\circ}\text{C}$, so a mixture would not behave like the cards alone predict.

Also acceptable: None.

- The oxygen tank contains liquid; the nitrogen tank is still all gas
- Compares $-190\text{ }^{\circ}\text{C}$ with both boiling points

8. Draw two particle boxes side by side: helium at $25\text{ }^{\circ}\text{C}$ and iron at $25\text{ }^{\circ}\text{C}$. Show spacing and motion, and add a one-line label under each box that says how strongly its particles attract.

Answer: Helium box: a few circles spread far apart, with long straight motion lines; label 'very weak attractions'. Iron box: circles packed in a regular pattern, touching, with short wiggle lines; label 'very strong attractions'.

Why: At $25\text{ }^{\circ}\text{C}$ helium is a gas and iron is a solid; the drawing should show the difference in spacing and motion that the attraction strengths produce.

Also acceptable: Accept arrows instead of motion lines.

- Helium shown as a gas: far apart, moving freely
- Iron shown as a solid: packed, ordered, vibrating
- Attraction labels correct

9. Methane and water are made of molecules of about the same mass, but at $25\text{ }^{\circ}\text{C}$ one is a gas and the other is a liquid. Explain why, using what happens to particles when a substance takes in thermal energy, and the idea of attractions between particles.

Answer: When any substance takes in thermal energy, its particles move more energetically, and once they have enough energy to overcome the attractions holding them together, they separate into a gas. Methane molecules attract one another weakly, so they separate at a very low temperature (methane boils at about $-162\text{ }^{\circ}\text{C}$) and are already a gas at $25\text{ }^{\circ}\text{C}$. Water molecules attract one another much more strongly, so at $25\text{ }^{\circ}\text{C}$ most of them do not have enough energy to pull apart; water must reach $100\text{ }^{\circ}\text{C}$ to boil. The difference is the strength of the attractions, not the mass of the molecules.

Why: Card 4 and Card 7 set up this comparison so that molecule mass is ruled out as the cause.

Also acceptable: Accept 'water molecules are stickier' as the attraction idea if the energy link is present.

- Links gaining thermal energy to particles overcoming attractions
- States that water's attractions are much stronger than methane's
- Uses the boiling points as evidence
- Rules out molecule mass as the cause

Scoring rubric

Criterion	4 • Exemplary	3 • Proficient	2 • Developing	1 • Beginning
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Expert teaching	Every expert's notes are accurate and each member teaches their three substances, including any special case, so the whole group can use them.	Notes are accurate, but one expert's teaching leaves out a special case or a value.	Notes have errors or one expert did not teach their cards.	The group worked from the cards without an expert round.
Group record and ladder	Ladder in correct order with carbon dioxide handled correctly; at least 34 of 36 state cells correct.	Ladder correct; 30 to 33 state cells correct.	Ladder has two or more substances out of place, or fewer than 30 cells correct.	Ladder or record missing.
Explaining the pattern	Explains that stronger attractions need more energy to overcome and so raise boiling points, and offers a sound reason for at least one melting-point swap.	Explains the attraction link but not the swap.	States that higher boiling points mean 'stronger' without saying why.	No explanation, or explains with particle size or mass alone.
Individual accountability	Part C answers are correct and each uses specific values from the cards.	Three of the four Part C answers are correct with values.	Two Part C answers are correct, or answers lack values.	Fewer than two Part C answers are correct.

Teacher notes

All values on the cards are real, rounded, and given at normal air pressure (sources: standard reference tables; helium cannot be solidified at normal pressure; carbon dioxide's triple point lies above five times normal pressure). Copper's boiling point is given as about 2,560 °C and iron's as about 2,860 °C; published values differ by a few degrees. The swaps in q4 are an honest limit of the attraction model: boiling points track attraction strength more closely than melting points, which also depend on how particles pack in the solid. Do not let students handle mercury, dry ice or any cryogenic liquid; the cards are the only materials.

Scaffold offered to students: Reading a melting point and a boiling point

A substance is solid below its melting point, liquid between its melting point and its boiling point, and gas above its boiling point (at normal air pressure). Draw a short number line for any substance you are unsure of: mark its melting point and boiling point, then mark the temperature you are testing and see which zone it lands in. Remember that −150 °C is colder than −100 °C.

Extension: Getting oxygen out of the air

Factories make liquid oxygen and liquid nitrogen by cooling air until it turns liquid and then letting it warm up slowly. Use the boiling points on Cards 2 and 3 to explain which gas boils off first as the liquid air warms, and how this could be used to separate the two. Then predict where argon (boiling point about −186 °C) would come off, and explain why separating argon from oxygen is harder than separating nitrogen from oxygen.