Lectures: Physics 3306

Provides an introduction to a wide variety of topics in classical (pre-quantum) physics as a bridge to prepare students for subsequent upper-level courses in physics. The topics covered include thermodynamics, fluid mechanics, mechanical waves, optics, radiation, electromagnetic phenomena, atoms, and laboratory techniques. Prerequisites: C- or better in PHYS 1106; and in PHYS 1304 or PHYS 1308.

Saptaparna Bhattacharya

February 27th, 2026

Based on Simon Dalley's lectures taught in Spring 2025

Labs

Lectures

Schedule

No class

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
January	19	20	21 ✅	22	23 ✅	24	25
	26 ❄️🌨️❄❄❄	27	28 ❄️🌨️❄❄❄	29	30 ✅	31	1
February	2 ✅	3	4 ✅	5	6 ✅	7	8
	9 ✅	10	11 HWB due	12	13 ✅	14	15
	16 ✅	17	18	19	20 HWC due ✅	21	22
	23 Hegi Center ✅	24	25 HWD due ✅	26	27 ✅	28	1
March	2	3	4 HWE due	5	6	7	8
	9	10	11	12	13	14	15
	16	17	18	19	20	21	22
	23	24	25	26	27	28	29
April	30	31	1	2	3	4	5

Labs

Lectures

Schedule

No class

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
April	6	7	8	9	10	11	12
	13	14	15	16	17	18	19
	20	21	22	23	24	25	26
May	27	28	29	30	1	2	3
	4	5	6	7	8	9	10

TEMPERATURE
Halliday 18.1-18.4

Key concepts: temperature

Temperature:

- Temperature is an SI base quantity related to our sense of hot and cold. It is measured with a thermometer, which contains a working substance with a measurable property, such as length or pressure, that changes in a regular way as the substance becomes hotter or colder
- Zeroth law of thermodynamics:
  - If bodies *A* and *B* are each in thermal equilibrium with a third body *T*, then *A* and *B* are in thermal equilibrium with each other

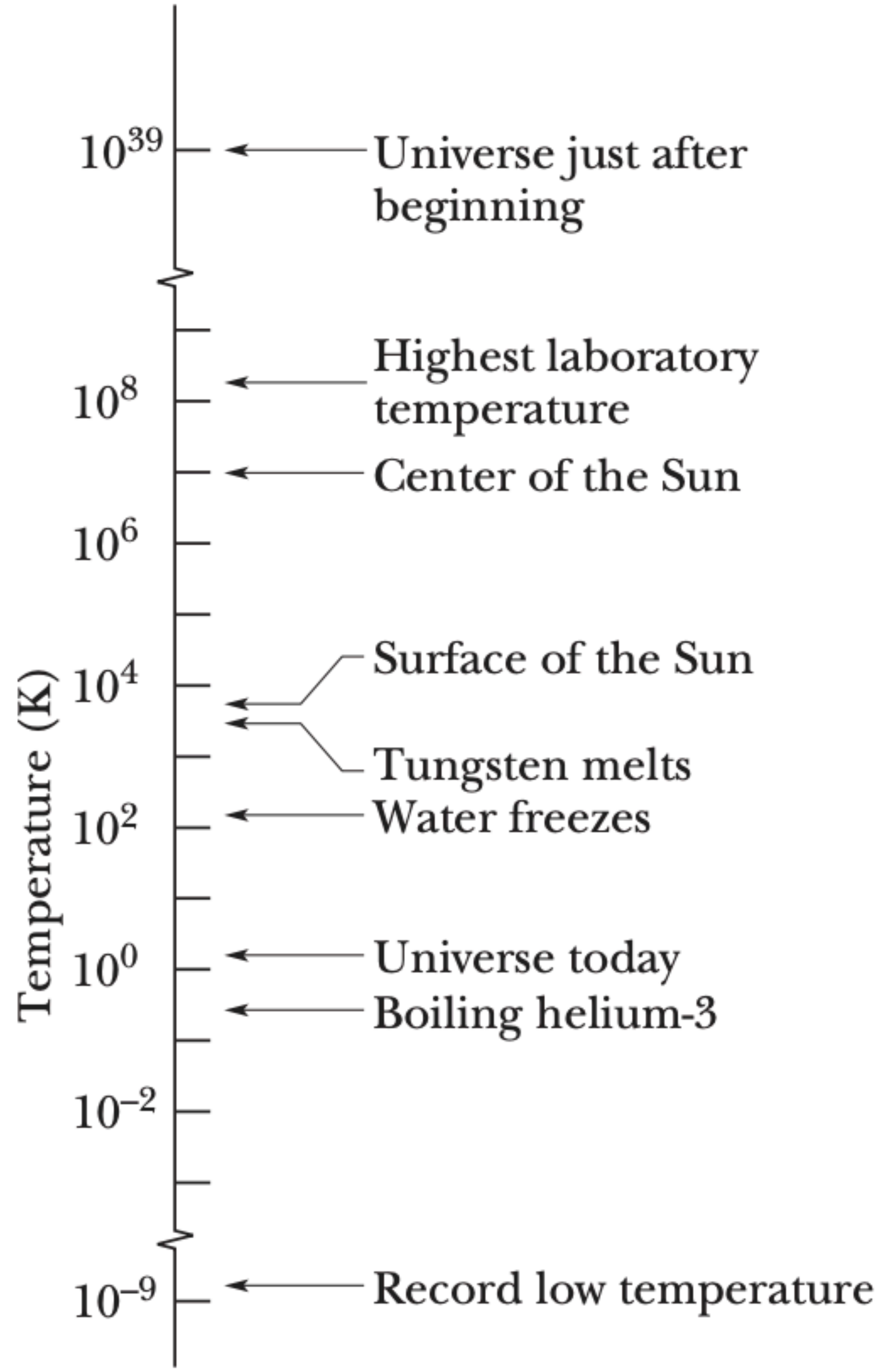
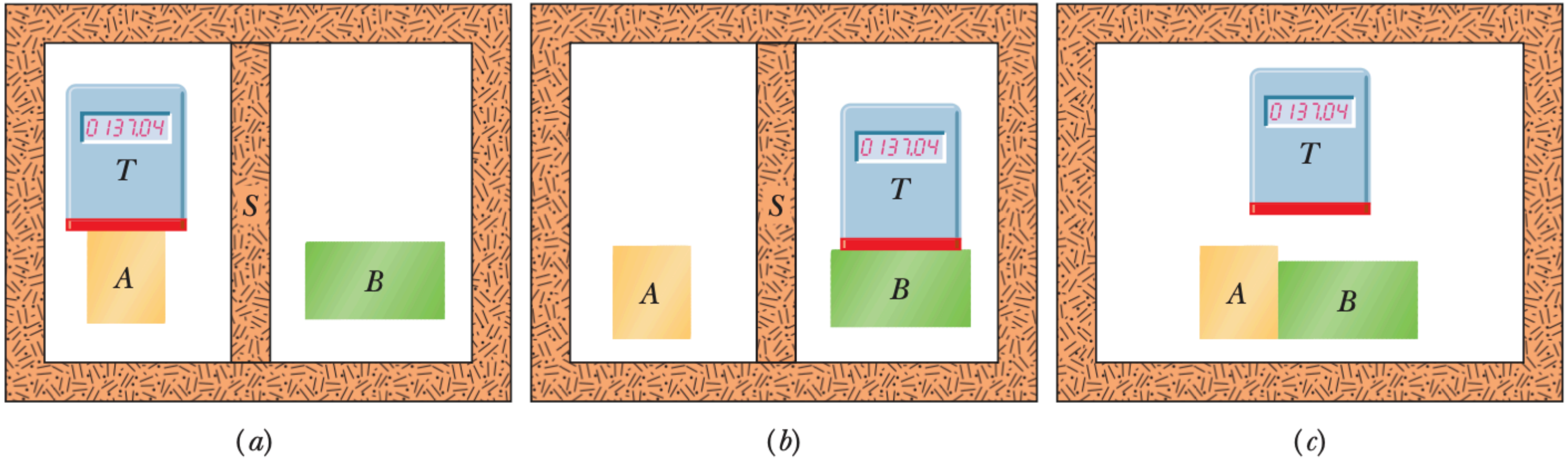


Figure 18-1 Some temperatures on the Kelvin scale. Temperature $T = 0$ corresponds to $10^{-\infty}$ and cannot be plotted on this logarithmic scale.

Key concepts: temperature

- Zeroth law of thermodynamics:
  - If bodies *A* and *B* are each in thermal equilibrium with a third body *T*, then *A* and *B* are in thermal equilibrium with each other

Figure 18-3 (*a*) Body *T* (a thermoscope) and body *A* are in thermal equilibrium. (Body *S* is a thermally insulating screen.) (*b*) Body *T* and body *B* are also in thermal equilibrium, at the same reading of the thermoscope. (*c*) If (*a*) and (*b*) are true, the zeroth law of thermodynamics states that body *A* and body *B* are also in thermal equilibrium.



Key concepts: measuring temperature

- Triple point of water: To set up a temperature scale, we pick some reproducible thermal phenomenon and, quite arbitrarily, assign a certain Kelvin temperature to its environment; that is, we select a *standard fixed point* and give it a standard fixed-point *temperature*. We could, for example, select the freezing point or the boiling point of water but, for technical reasons, we select instead the **triple point of water**
- Liquid water, solid ice, and water vapor (gaseous water) can coexist, in thermal equilibrium, at only one set of values of pressure and temperature.

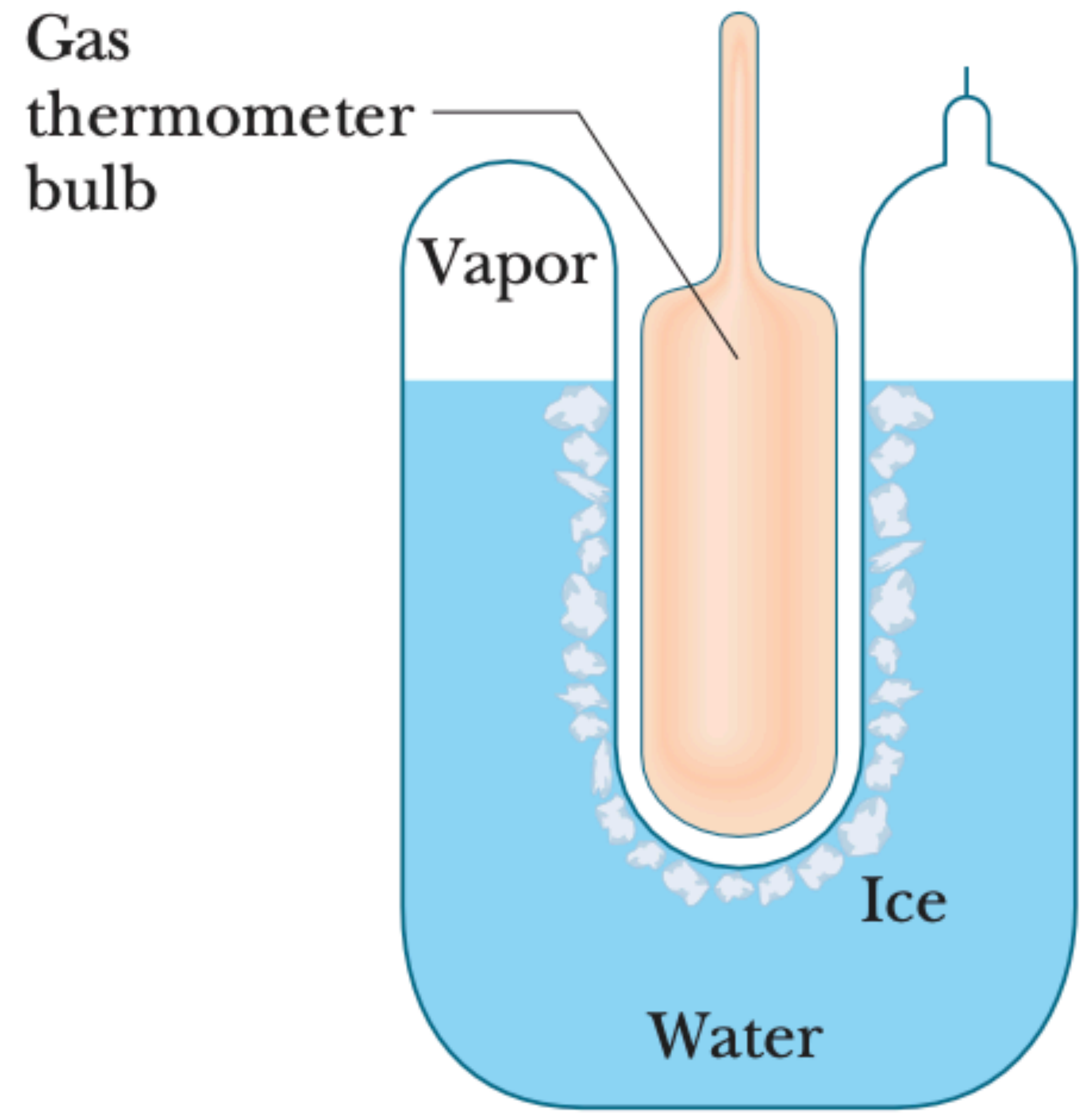
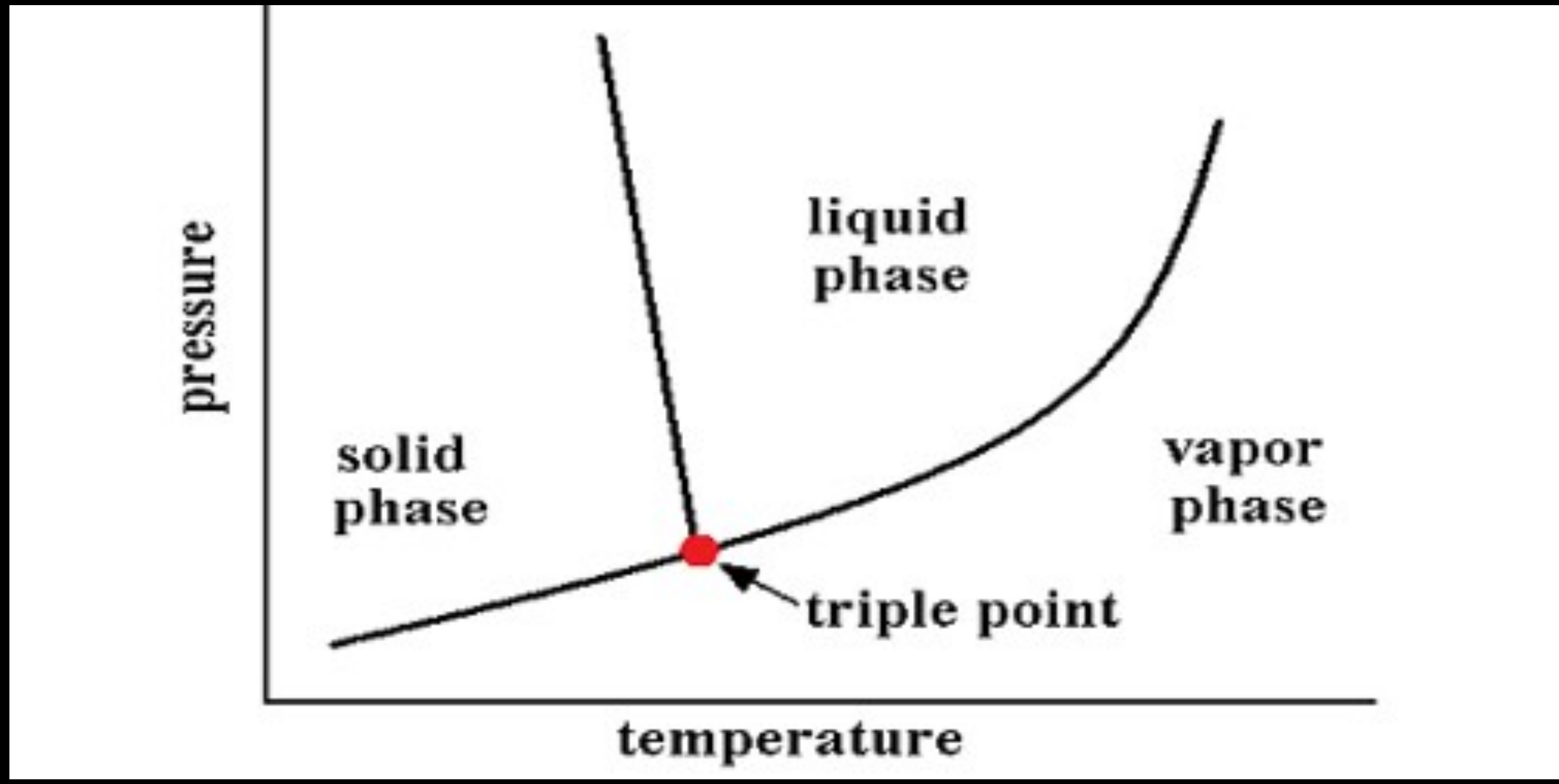


Figure 18-4 A triple-point cell, in which solid ice, liquid water, and water vapor coexist in thermal equilibrium. By international agreement, the temperature of this mixture has been defined to be 273.16 K. The bulb of a constant-volume gas thermometer is shown inserted into the well of the cell.

Key concepts: measuring temperature

- Triple point of water:
  - By international agreement, the triple point of water has been assigned a value of 273.16 K as the standard fixed-point temperature for the calibration of thermometers; that is
  - $T_3 = 273.16\ K$



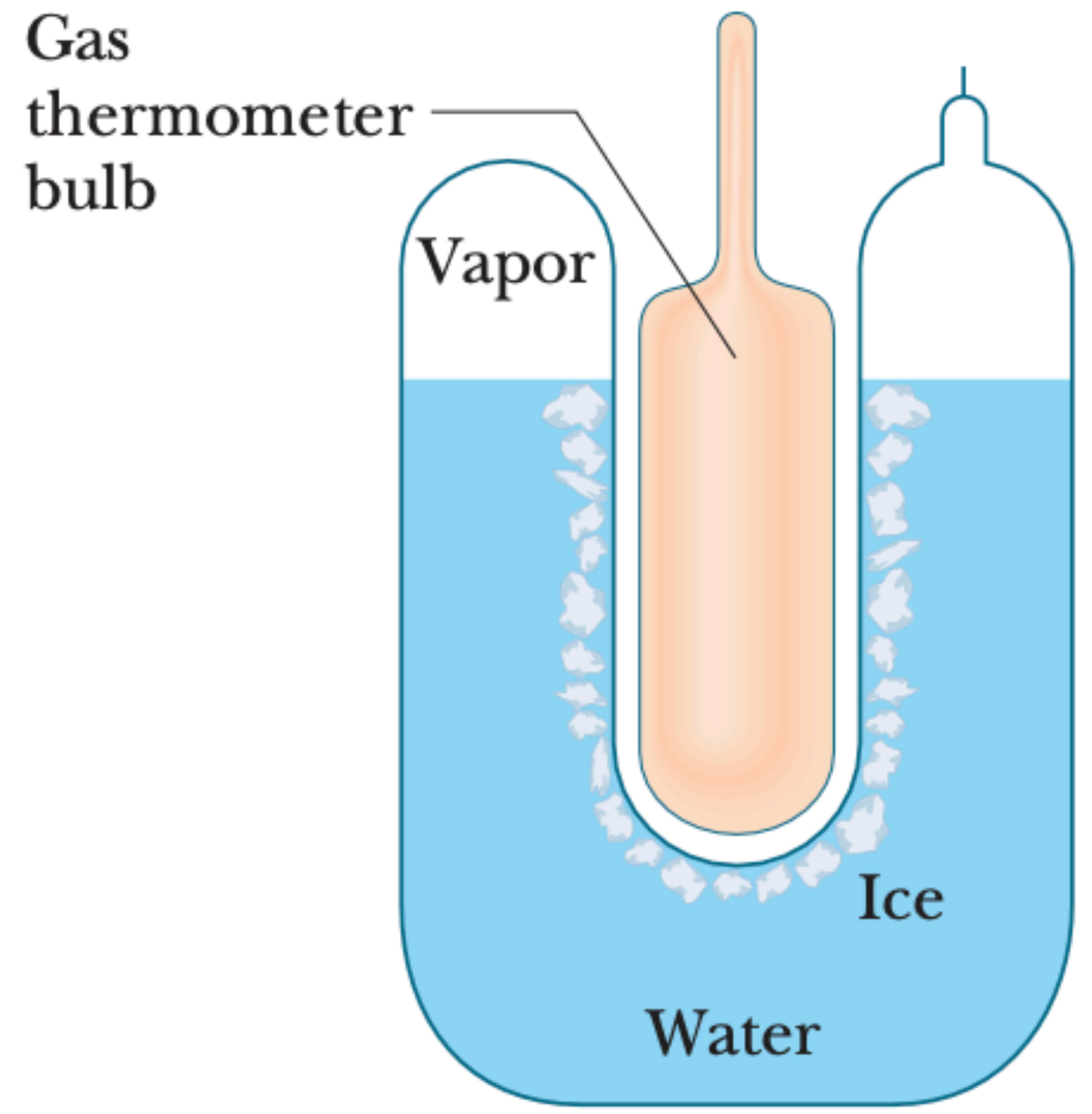


Figure 18-4 A triple-point cell, in which solid ice, liquid water, and water vapor coexist in thermal equilibrium. By international agreement, the temperature of this mixture has been defined to be 273.16 K. The bulb of a constant-volume gas thermometer is shown inserted into the well of the cell.

Key concepts: measuring temperature

- Constant-Volume Gas Thermometer
  - the standard thermometer, against which all other thermometers are calibrated, is based on the pressure of a gas in a fixed volume
  - consists of a gas-filled bulb connected by a tube to a mercury manometer
  - The temperature of any body in thermal contact with the bulb is:
    - $T = Cp$, $p =$ pressure exerted by gas, $C =$ constant
    - The pressure is:
      - $p = p_0 - h\rho g$ (p_0 = atmospheric pressure)
      - minus sign is used because pressure p is measured *above* the level at which the pressure is p_0

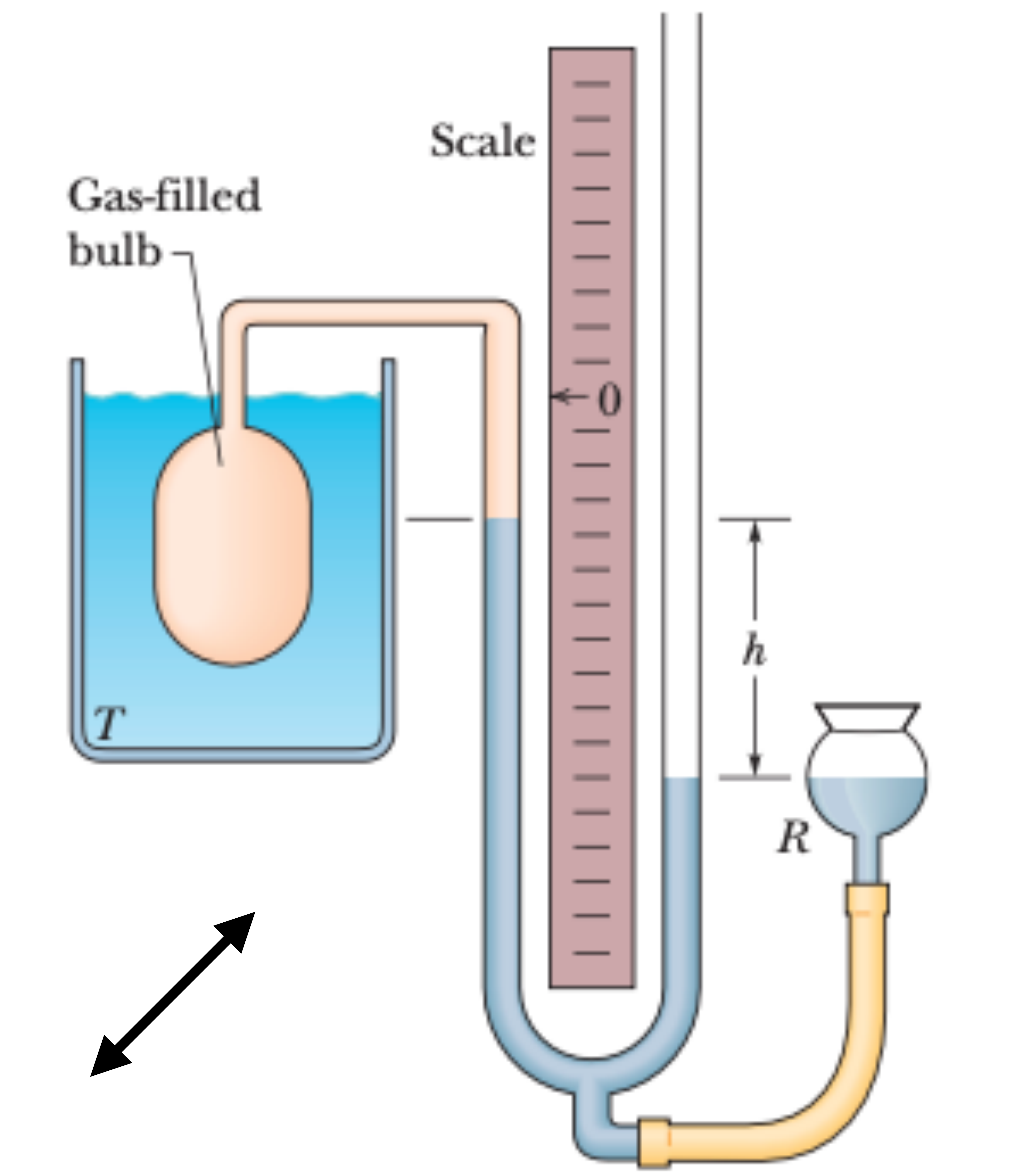


Figure 18-5 A constant-volume gas thermometer, its bulb immersed in a liquid whose temperature T is to be measured.

Key concepts: measuring temperature

- Constant-Volume Gas Thermometer
  - Putting the next bulb in a triple-point cell, the temperature is:
    - $T_3 = Cp_3$
    - Eliminating C:
    - $$T = T_3\left(\frac{p}{p_3}\right) = (273.16\ K)\left(\frac{p}{p_3}\right)$$
    - ⚠️If we use it to measure, say, the boiling point of water, we find that different gases in the bulb give slightly different results. However, as we use smaller and smaller amounts of gas to fill the bulb, the readings converge nicely to a single temperature, no matter what gas we use

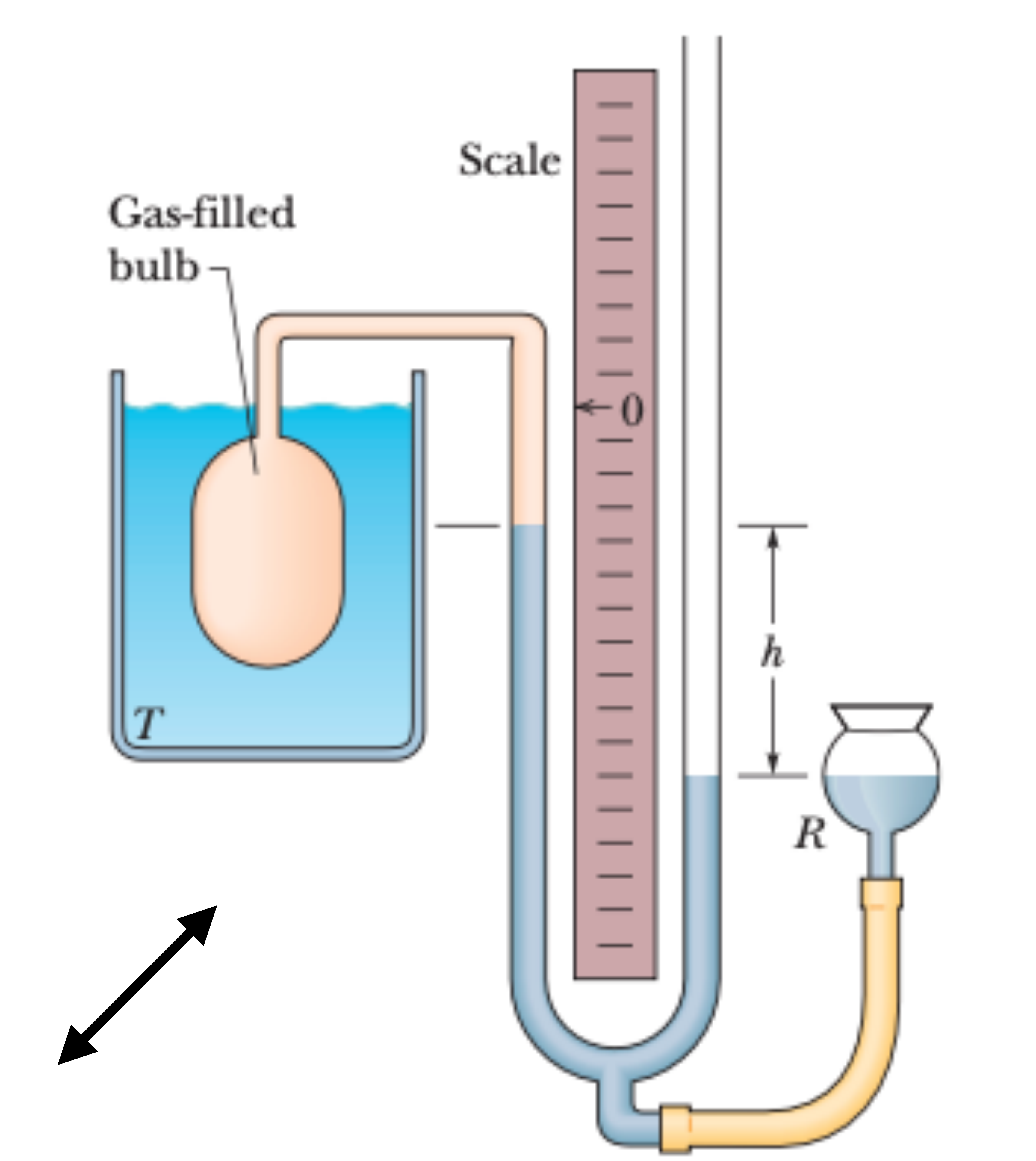
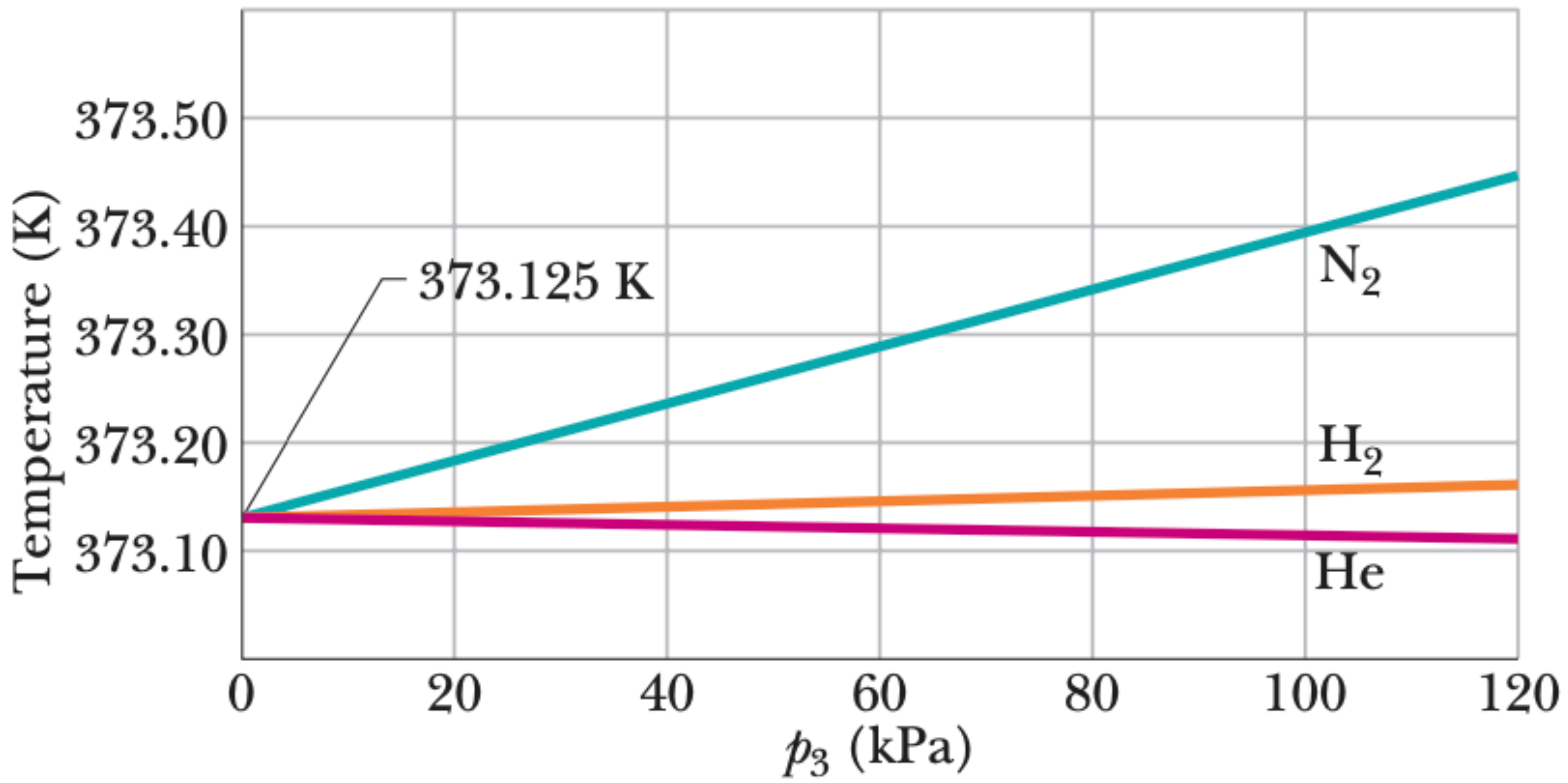


Figure 18-5 A constant-volume gas thermometer, its bulb immersed in a liquid whose temperature T is to be measured.

Key concepts: measuring temperature

- Constant-Volume Gas Thermometer
- $$T = T_3\left(\frac{p}{p_3}\right) = (273.16\ K)\left(\frac{p}{p_3}\right)$$
- For smaller and smaller amount of gas:
  - $$T = (273.16\ K)\left(\lim_{\text{gas}\to 0}\frac{p}{p_3}\right)$$

Figure 18-6 Temperatures measured by a constant-volume gas thermometer, with its bulb immersed in boiling water. For temperature calculations using Eq. 18-5, pressure p_3 was measured at the triple point of water. Three different gases in the thermometer bulb gave generally different results at different gas pressures, but as the amount of gas was decreased (decreasing p_3), all three curves converged to 373.125 K.



Rank the following 4 samples according to their temperature T, greatest first, at their pressure shown and their Triple-point pressure

a) Pressure 2.6 kPa, Triple-point pressure 2.0 kPa
b) Pressure 4.8 kPa, Triple-point pressure 4.0 kPa
c) Pressure 5.5 kPa, Triple-point pressure 5.0 kPa
d) Pressure 7.2 kPa, Triple-point pressure 6.0 kPa

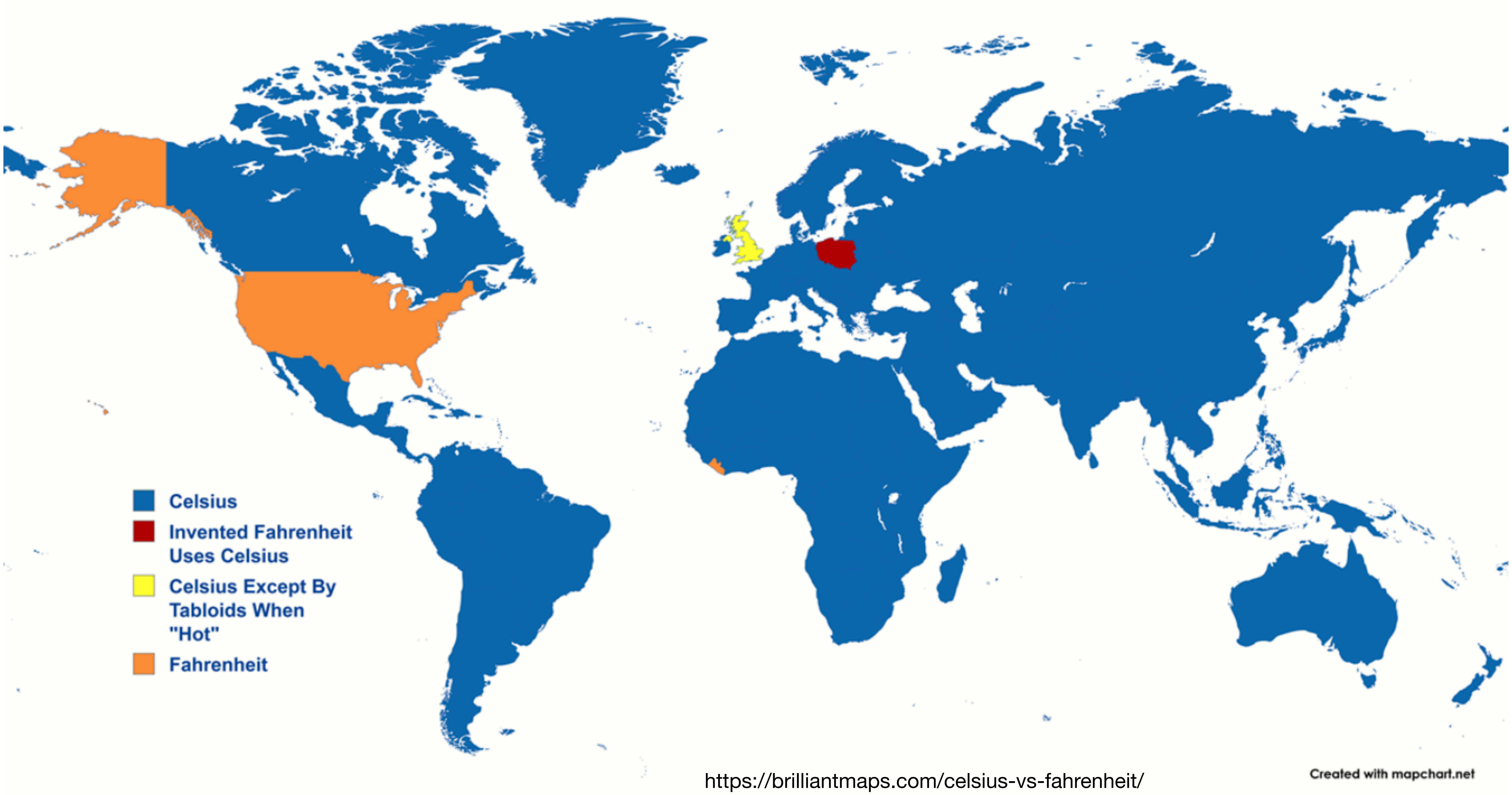
1. a > b > c > d
2. a > b = d > c
3. d > c > b > a
4. a = b = c = d
5. c > d = b > a

Rank the following 4 samples according to their temperature T, greatest first, at their pressure shown and their Triple-point pressure

a) Pressure 2.6 kPa, Triple-point pressure 2.0 kPa (2.6/2.0 = 1.3)
b) Pressure 4.8 kPa, Triple-point pressure 4.0 kPa (4.8/4.0 = 1.2)
c) Pressure 5.5 kPa, Triple-point pressure 5.0 kPa (5.5/5.0 = 1.1)
d) Pressure 7.2 kPa, Triple-point pressure 6.0 kPa (7.2/6.0 = 1.2)

1. a > b > c > d
2. a > b = d > c
3. d > c > b > a
4. a = b = c = d
5. c > d = b > a

$$T = T_3\left(\frac{p}{p_3}\right)$$



https://brilliantmaps.com/celsius-vs-fahrenheit/

Key concepts: scales

- The Celsius scale is defined by:
  - $T_C = T - 273.15°$, T is in Kelvins
- The Fahrenheit scale is defined by:
  - $T_F = \frac{9}{5}T_C + 32°$

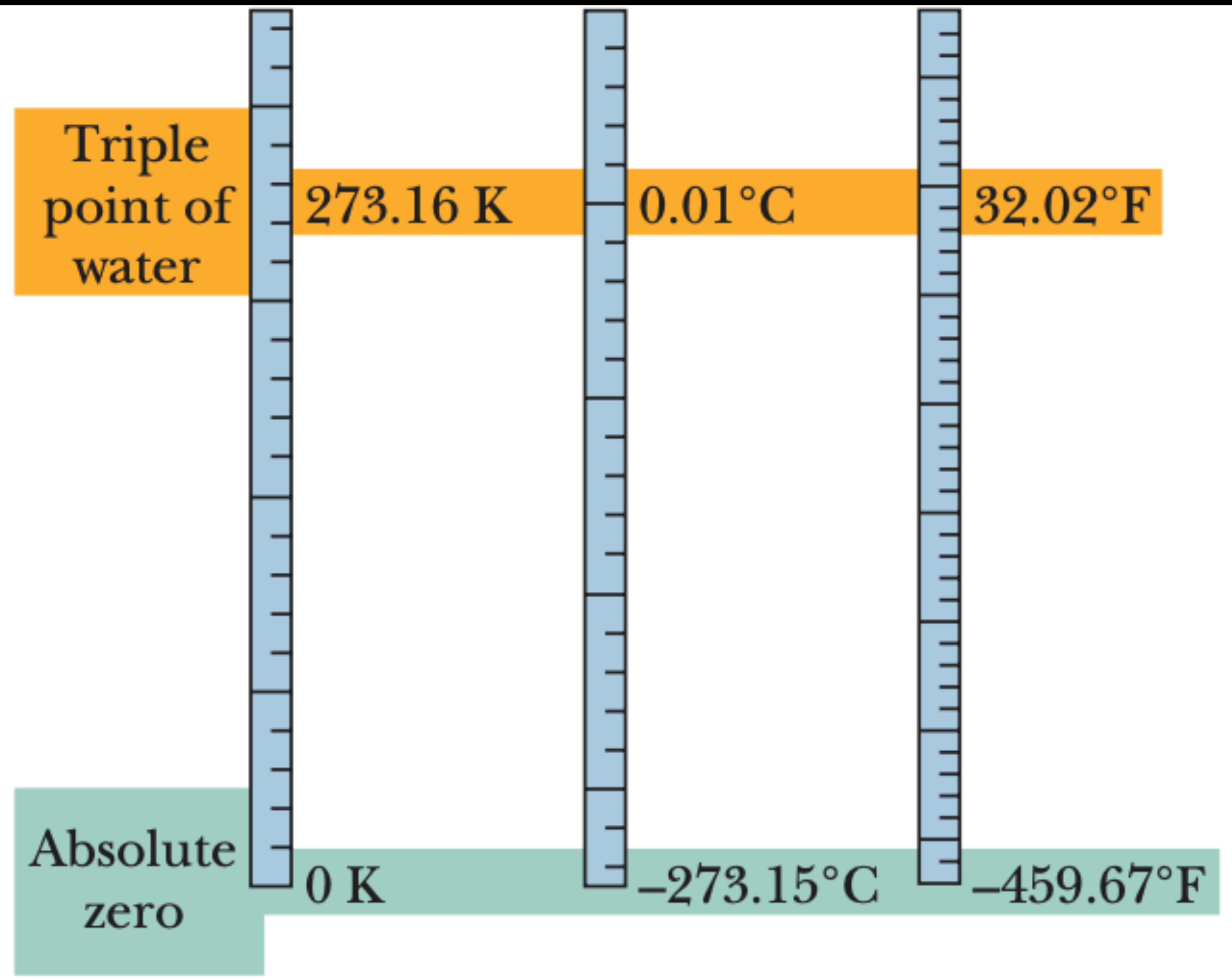


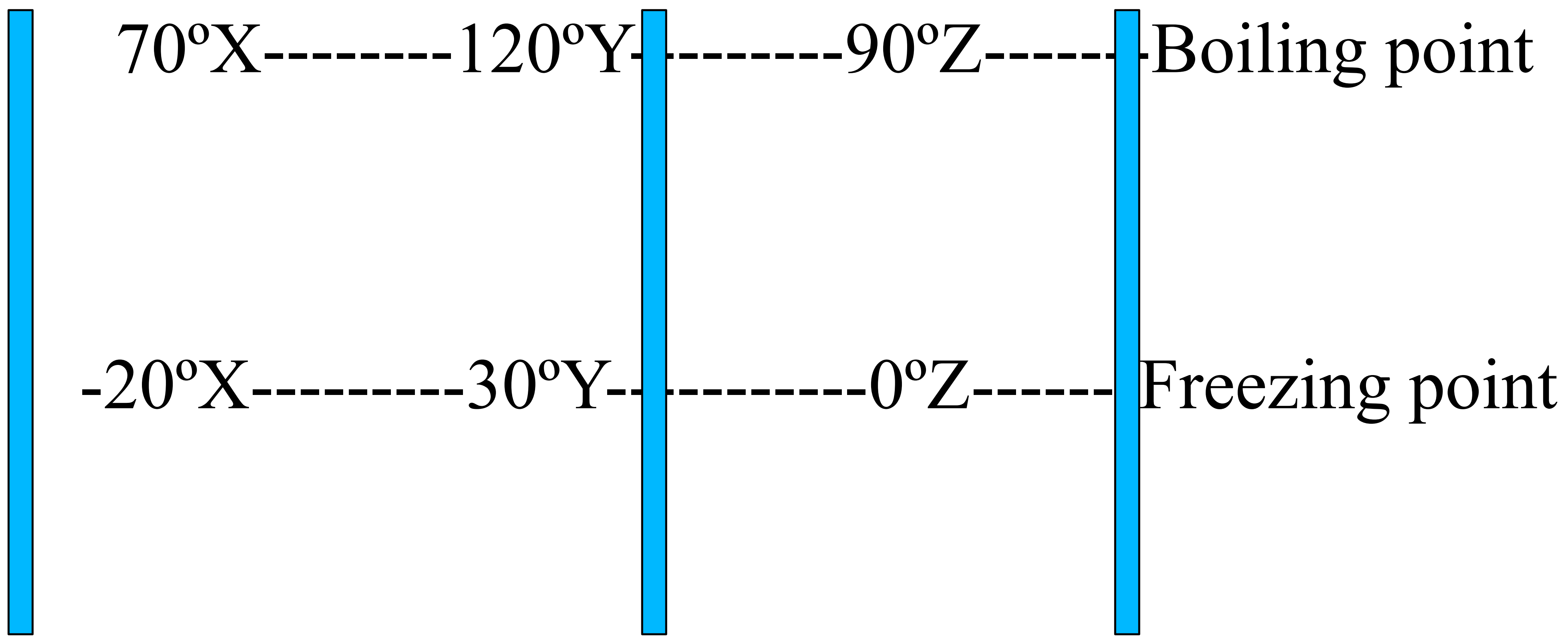
Figure 18-7 The Kelvin, Celsius, and Fahrenheit temperature scales compared.

Table 18-1 Some Corresponding Temperatures

Temperature	°C	°F
Boiling point of water[a]	100	212
Normal body temperature	37.0	98.6
Accepted comfort level	20	68
Freezing point of water[a]	0	32
Zero of Fahrenheit scale	≈ −18	0
Scales coincide	−40	−40

[a]Strictly, the boiling point of water on the Celsius scale is 99.975°C, and the freezing point is 0.00°C. Thus, there is slightly less than 100 C° between those two points.

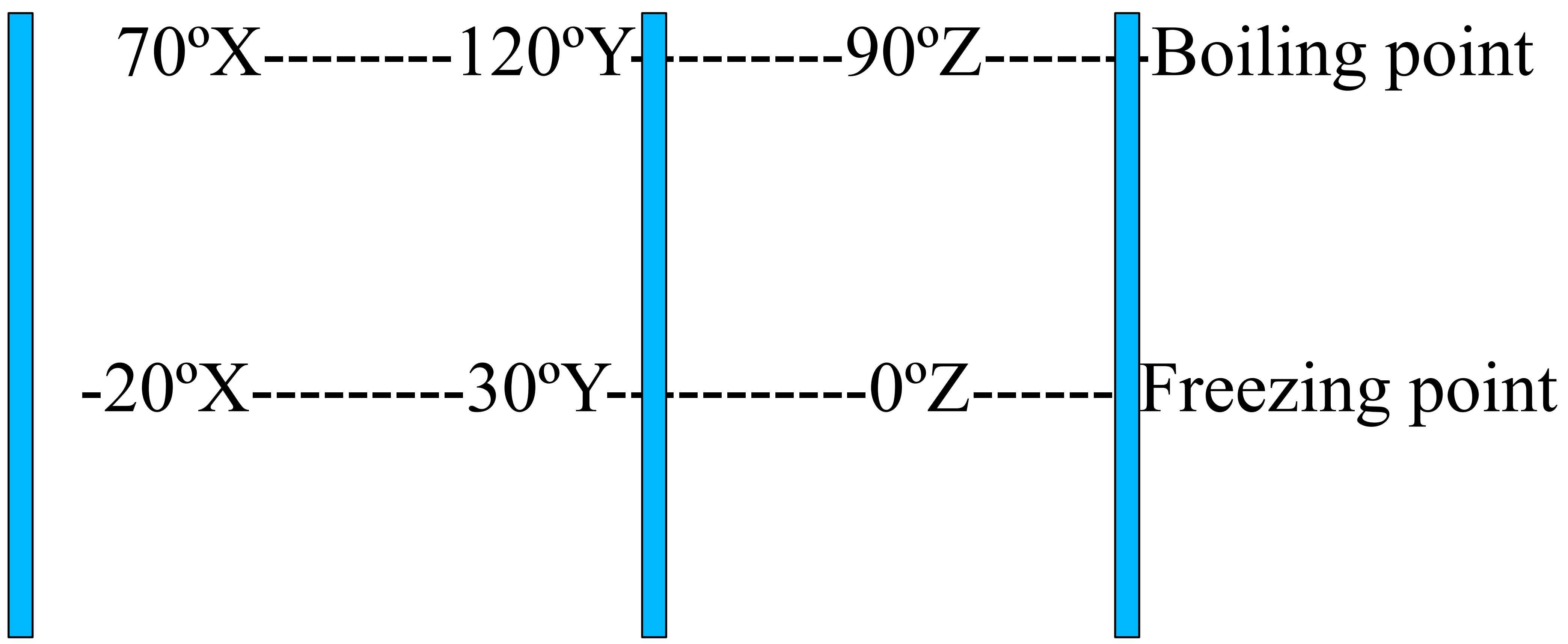
The figure shows three linear temperature scales with the freezing and boiling points of water indicated.



Rank the temperature 50º, highest first

1. X > Z > Y
2. Z > Y > X
3. Y > Z > X
4. Z > X > Y
5. Y > X > Z

The figure shows three linear temperature scales with the freezing and boiling points of water indicated.



Rank the temperature 50º, highest first

1. X > Z > Y
2. Z > Y > X
3. Y > Z > X
4. Z > X > Y
5. Y > X > Z

Step 1: Find the degree size for each scale
First, we need to calculate the range between the boiling and freezing points of water for each temperature scale. This will tell us how "large" one degree is on that scale.

- **Scale X:** 70°X - (-20°X) = 90 degrees
- **Scale Y:** 120°Y - 30°Y = 90 degrees
- **Scale Z:** 90°Z - 0°Z = 90 degrees

Because all three scales span exactly 90 degrees between the freezing and boiling points, a change of one degree represents the exact same physical temperature change on all three scales. The only difference between them is where their zero point is located.
Step 2: Determine the position relative to the freezing point
Since the "size" of a degree is identical across X, Y, and Z, we can find out which 50° mark is physically hottest by simply calculating how many degrees it is above the freezing point of water.

- **For 50°X:** 50 - (-20) = **70 degrees** above freezing.
- **For 50°Y:** 50 - 30 = **20 degrees** above freezing.
- **For 50°Z:** 50 - 0 = **50 degrees** above freezing.

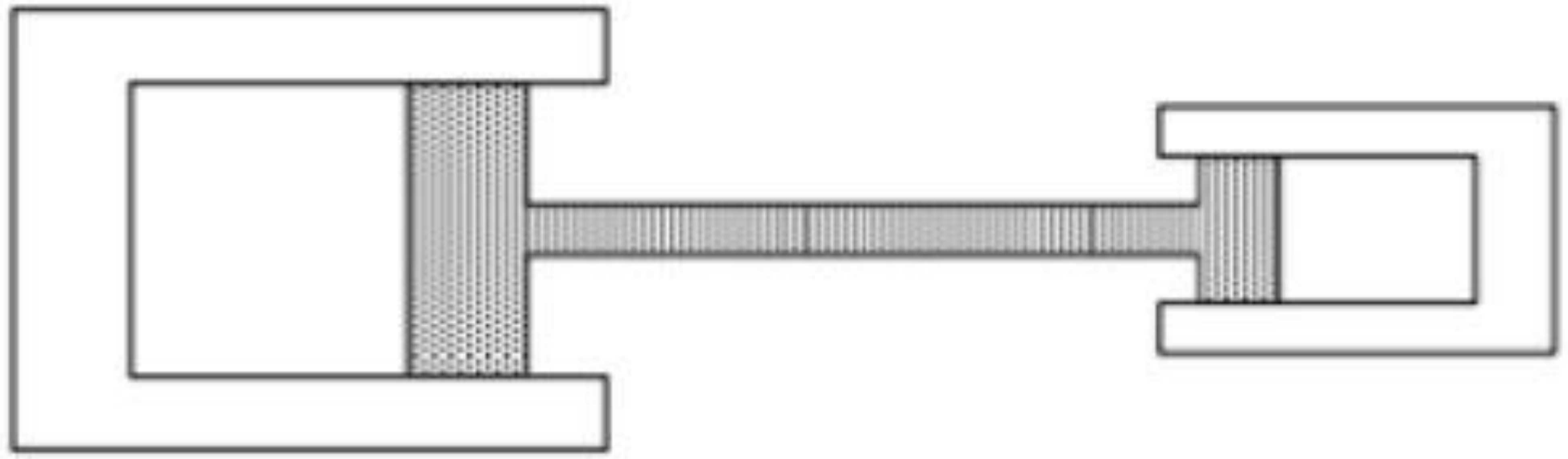
Step 3: Rank the temperatures
The value that sits the most degrees above the freezing point corresponds to the highest absolute temperature.

- **Highest:** 50°X (70 degrees above freezing)
- **Middle:** 50°Z (50 degrees above freezing)
- **Lowest:** 50°Y (20 degrees above freezing)

The correct ranking from highest to lowest is **X > Z > Y**.
This means the correct answer is **Option 1**.

If the pressure in each chamber is equal and friction is neglected, in which direction will the piston move?

Refer to the diagram and consider that the pressure in each chamber is equal. Determine the direction of movement of the piston. Prove and justify your answer using equations. (10 pts)



1. To the left

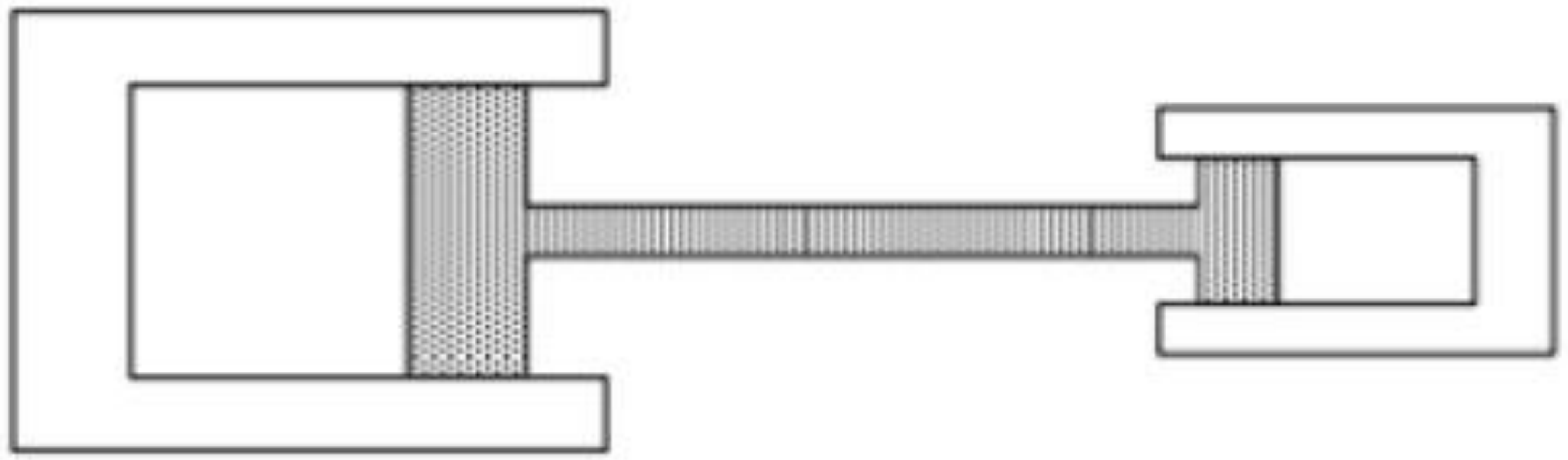
2. To the right

3. It won’t move

4. Not enough information

If the pressure in each chamber is equal and friction is neglected, in which direction will the piston move?

Refer to the diagram and consider that the pressure in each chamber is equal. Determine the direction of movement of the piston. Prove and justify your answer using equations. (10 pts)



1. To the left

2. To the right

3. It won’t move

4. Not enough information

The core concept to apply here is the relationship between pressure, force, and area. Pressure (P) is defined as the force (F) exerted per unit area (A).

The formula is:

$$P = AF$$

Which can be rearranged to solve for the force exerted by the gas on the piston:

$$F = P \times A$$

Analyzing the Forces

Let's break down the forces acting on the rigid, connected piston assembly:

1. **Left Piston:** Let's call the cross-sectional area of the left piston A_L. The gas in the left chamber exerts a force pushing the piston assembly to the **right**. We'll call this force F_L.
   $$F_L = P \times A_L$$
2. **Right Piston:** Let's call the cross-sectional area of the right piston AR . The gas in the right chamber exerts a force pushing the piston assembly to the **left**. We'll call this force FR .
   $$F_R = P \times A_R$$

Determining the Net Movement

The problem states that the pressure (P) is equal in both chambers. However, looking at the diagram, it is clear that the left piston has a significantly larger surface area than the right piston ($A_L > A_R$).

Because the pressure is identical but the area on the left is greater, the total force pushing from the left is greater than the total force pushing from the right:

$$P \times A_L > P \times A_R$$

$$F_L > F_R$$

There is a net force acting on the piston assembly to the right. Therefore, the piston will move to the right.

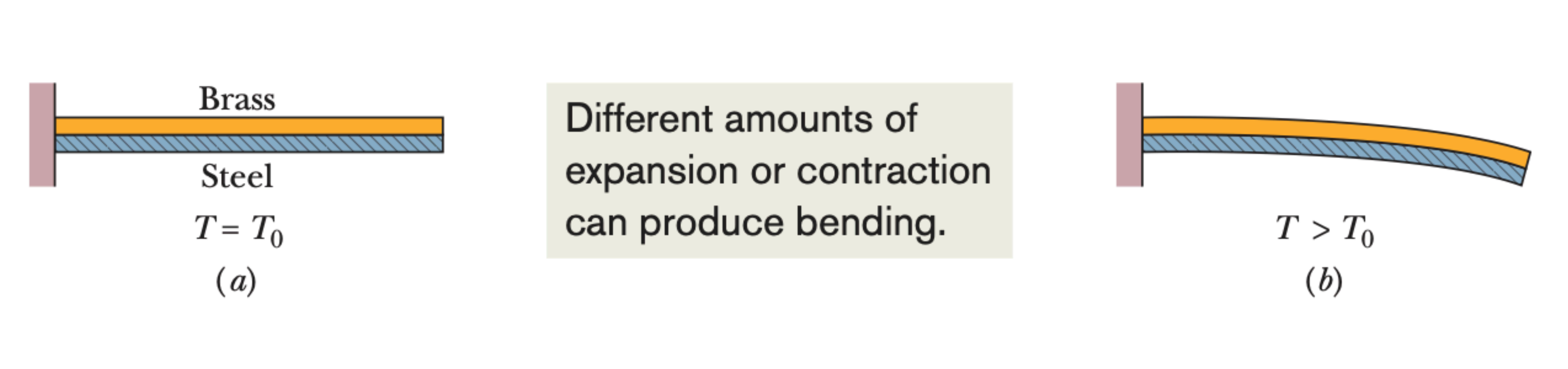
The correct answer is **Option 2: To the right**.

Key concepts: Thermal Expansion

- All objects change size with changes in temperature
- For a temperature change ΔT, a change ΔL in any linear dimension L is given by:
  - $\Delta L = L\alpha\Delta T$, α is the coefficient of linear expansion
- The change ΔV in a volume V of a solid or liquid is:
  - $\Delta V = V\beta\Delta T$
  - $\beta = 3\alpha$: material's coefficient of volume expansion

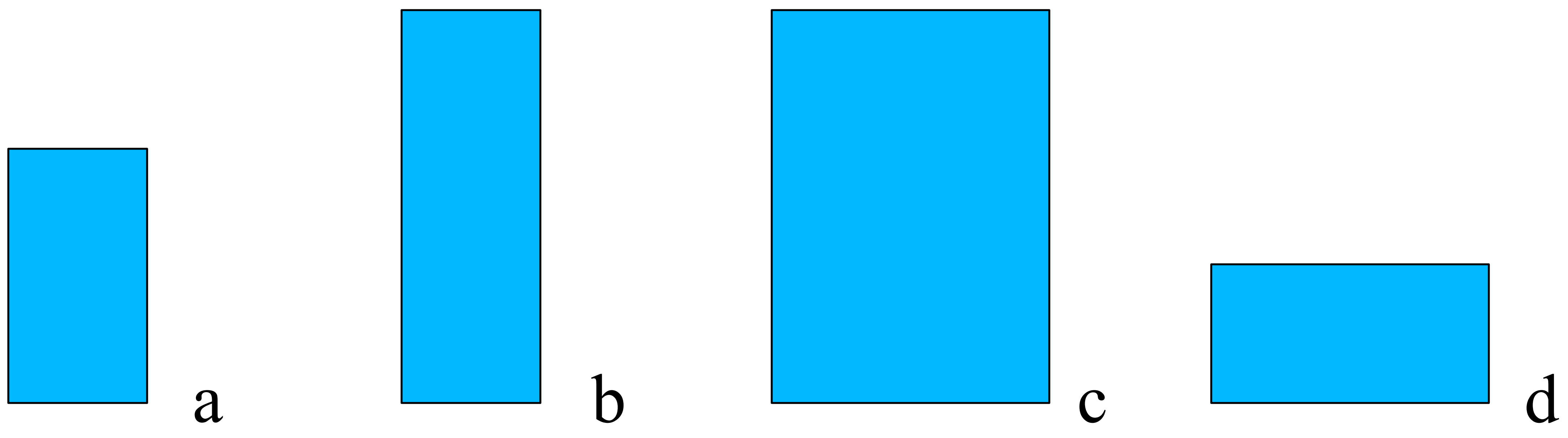
Key concepts: Thermal Expansion

- If the temperature of a metal rod of length L is raised by an amount ΔT, its length is found to increase by an amount:
    - $\Delta L = L\alpha\Delta T$



The figure shows 4 rectangular metal plates with sides of length L, 2L, or 3L, all made of the same material and whose temperature is raised by the same amount.

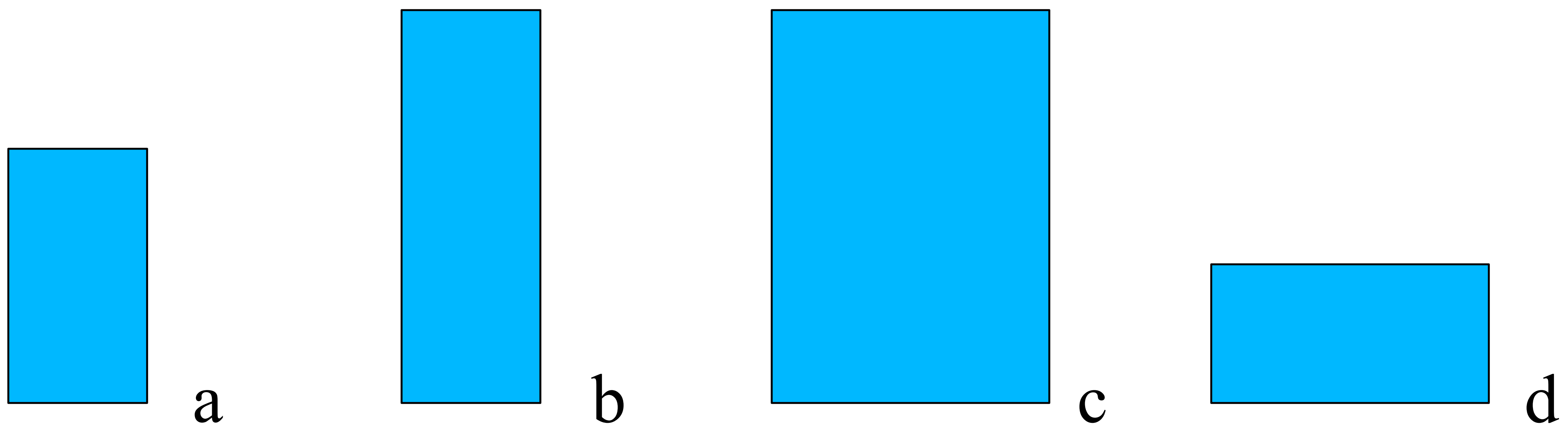
Rank them according to their expected increase in vertical height, greatest first



1.c > b > a > d
2.b > c > a > d
3.d > a > b = c
4.b = c > a > d
5.c > b > a > d

The figure shows 4 rectangular metal plates with sides of length L, 2L, or 3L, all made of the same material and whose temperature is raised by the same amount.

Rank them according to their expected increase in vertical height, greatest first



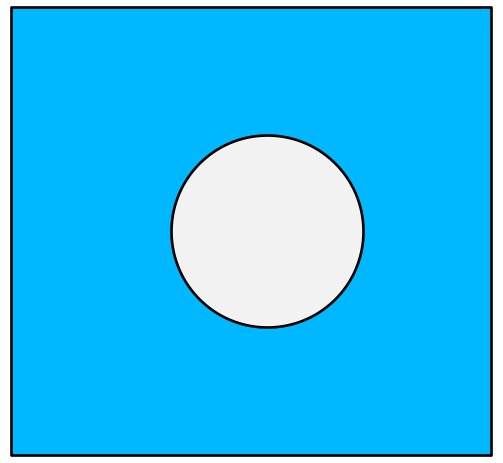
1. c > b > a > d
2. b > c > a > d
3. d > a > b = c
4. b = c > a > d
5. c > b > a > d

$$\Delta L = L\alpha\Delta T$$

- **Plate b** and **Plate c** clearly have the greatest initial vertical height (visually 3L). Because their initial heights are equal, their increase in height will also be equal (b=c).
- **Plate a** has the next greatest initial vertical height (visually 2L).
- **Plate d** has the smallest initial vertical height (visually L).

Ranking them from greatest expected increase to least, we get: **b=c>a>d**

The figure shows a piece of metal with a hole cut out of it.
As the temperature of the metal is increased, the area of the hole



1. Increases

2. Decreases

3. Stays the same

4. It depends on the coefficient of thermal expansion

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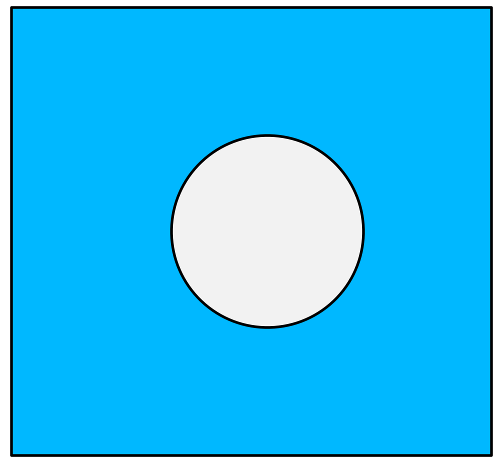


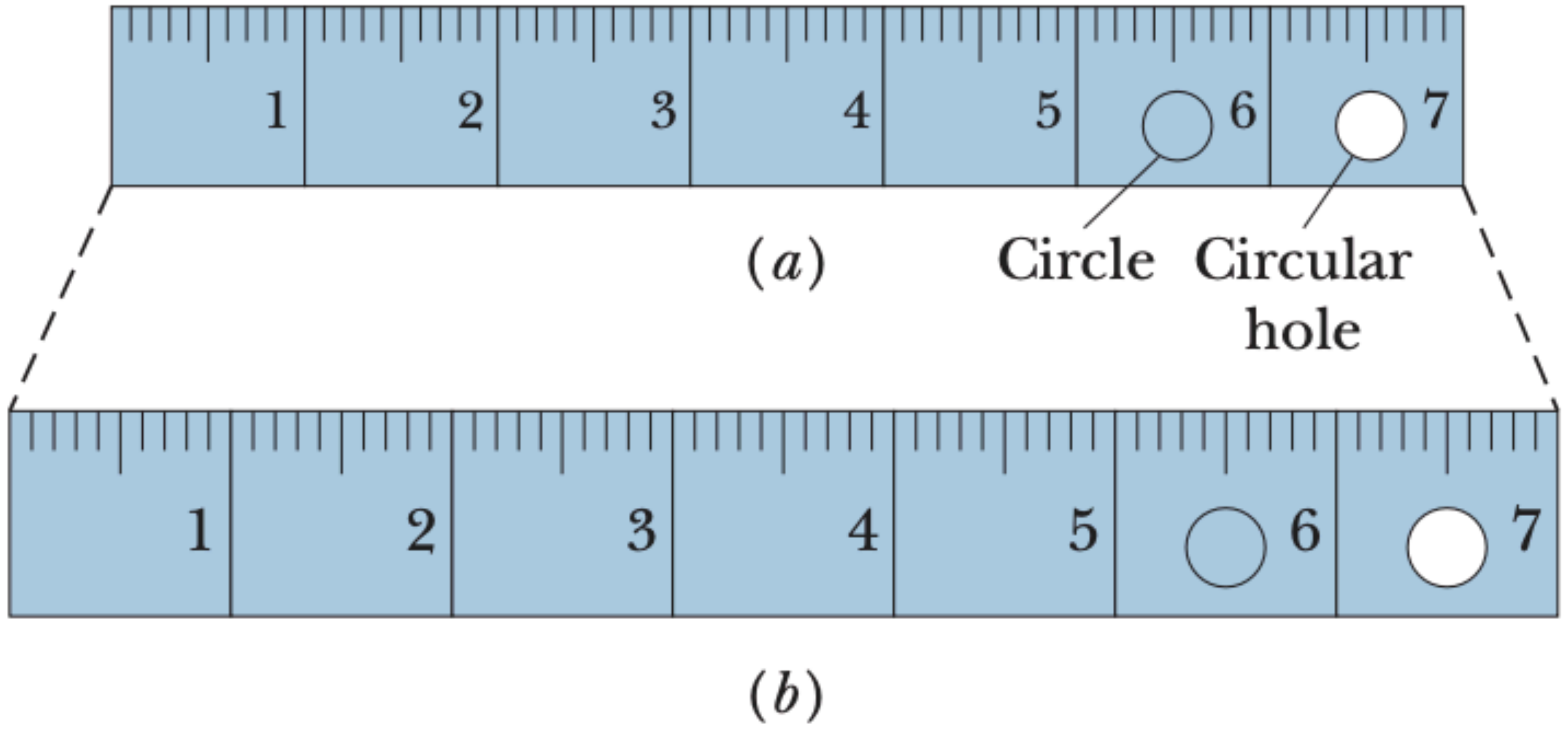
1.Increases

2.Decreases

3.Stays the same

4.It depends on the coefficient of thermal expansion

Figure 18-11 The same steel ruler at two different temperatures. When it expands, the scale, the numbers, the thickness, and the diameters of the circle and circular hole are all increased by the same factor. (The expansion has been exaggerated for clarity.)



Key concepts: Absorption of heat

- Heat Q is energy that is transferred between a system and its environment because of a temperature difference between them. It can be measured in joules (J), calories (cal), kilocalories (Cal or kcal), or British thermal units (Btu), with:
    - 1 cal = 3.968 $\times 10^{-3}$ Btu = 4.1868 J
- If heat Q is absorbed by an object, the object's temperature change $(T_f - T_i)$ is related to Q by:
    - $Q = C(T_f - T_i)$, C = heat capacity
    - $Q = cm(T_f - T_i)$, c = specific heat

Key concepts: Absorption of heat

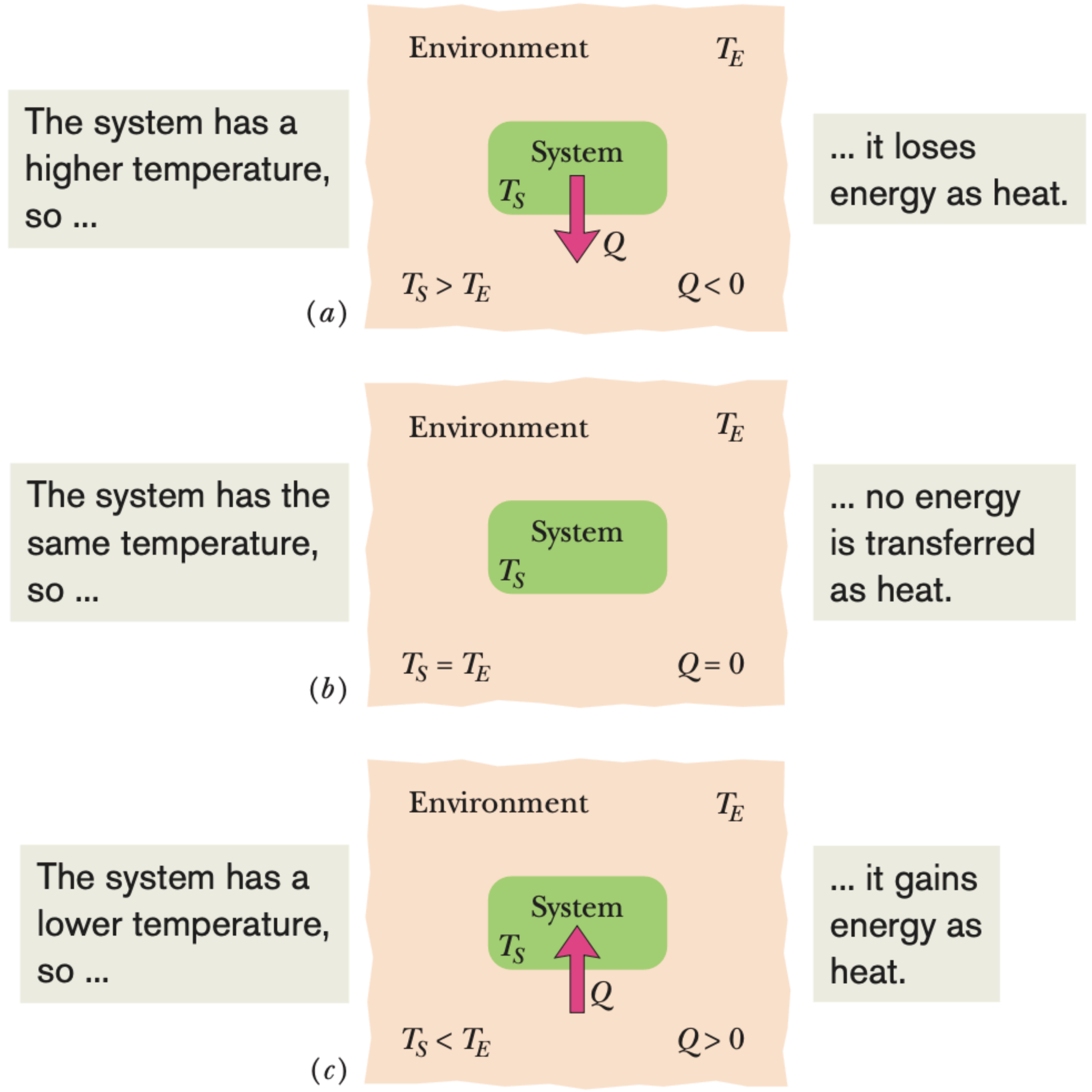


Figure 18-12 If the temperature of a system exceeds that of its environment as in (*a*), heat Q is lost by the system to the environment until thermal equilibrium (*b*) is established. (*c*) If the temperature of the system is below that of the environment, heat is absorbed by the system until thermal equilibrium is established.

Key concepts: What is heat?

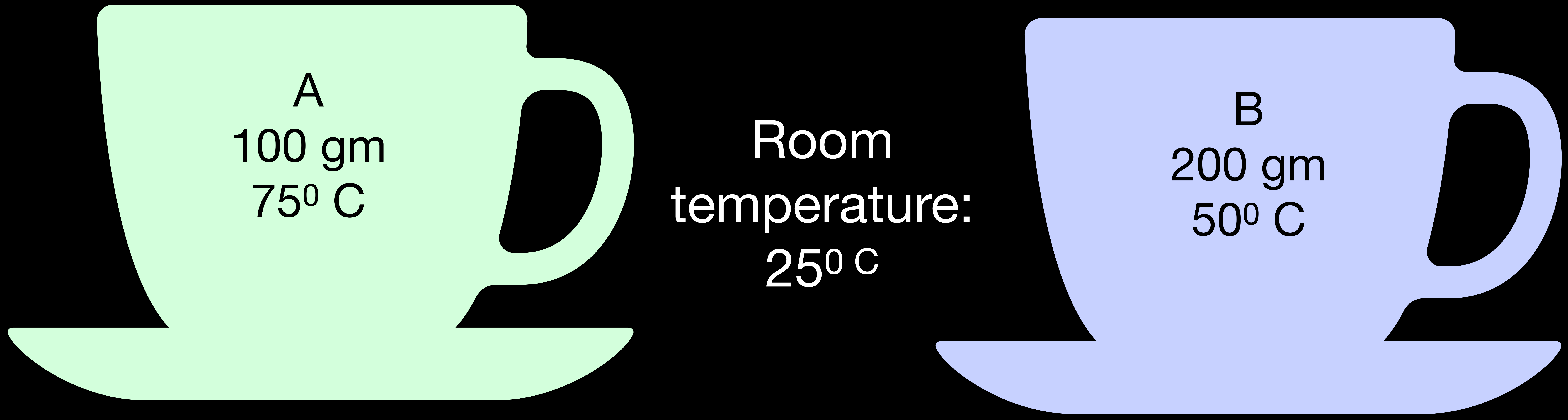
- Heat is the energy transferred between a system and its environment because of a temperature difference that exists between them

Key concepts: Absorption of heat

- Heat absorbed by a material may change the material's physical state — for example, from solid to liquid or from liquid to gas. The amount of energy required per unit mass to change the state (but not the temperature) of a particular material is its heat of transformation L.
  - $Q = Lm$
  - The heat of vaporization L_V is the amount of energy per unit mass that must be added to vaporize a liquid or that must be removed to condense a gas
  - The heat of fusion L_F is the amount of energy per unit mass that must be added to melt a solid or that must be removed to freeze a liquid

Cup A contains 100 grams of water and cup B contains twice as much water. The water in both cups was initially at room temperature. Then the water in cup A was heated to 75°C and the water in cup B was heated to 50°C. When the water in both cups cooled down to room temperature, which cup had more heat transferred from it?

A) Cup A had more heat transferred out.
B) Cup B had more heat transferred out.
C) Both cups had the same amount of heat transferred.
D) Not enough information is given to determine the answer.



The amount of heat (Q) transferred to or from a substance can be calculated using the specific heat capacity formula: $Q = mc\Delta T$
Where:

- Q is the total heat transferred.
- m is the mass of the substance.
- c is the specific heat capacity (which is the same for both cups since they both contain water).
- ΔT is the change in temperature $T_{initial} - T_{final}$

Calculating Heat Transferred for Each Cup
From the diagram, we can see that room temperature is 25∘C. Let's calculate the relative heat lost by each cup as they cool down to this temperature:
Cup A:

- Mass (m_A) = 100 g
- Change in temperature (ΔT_A) = 75∘C−25∘C=50∘C
- Heat transferred (Q_A) = 100 g×c×50∘C=5000c

Cup B:

- Mass (m_B) = 200 g
- Change in temperature (ΔT_B) = 50∘C−25∘C=25∘C
- Heat transferred (Q_B) = 200 g×c×25∘C=5000c

Comparing the Results
As we can see from the calculations, both Cup A and Cup B transfer the exact same amount of thermal energy (5000c) to their surroundings as they cool down to room temperature. Cup A has half the mass but undergoes twice the temperature change, perfectly balancing out Cup B, which has twice the mass but undergoes half the temperature change.
The correct answer is C) Both cups had the same amount of heat transferred.

When heating a solution, its temperatures increases during a period of time.

Which of the following statements accurately characterizes the solution during this period?

1. The solution is at boiling point.

2. The solution is undergoing a phase change.

3. The solution's temperature increase is proportional to the Latent Heat L_v

4. All of the above

5. The velocity of molecules in the solution is increasing.

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4. All of the above

5. The velocity of molecules in the solution is increasing.

The key to this problem is understanding the physical definition of temperature. Macroscopically, temperature is what we measure with a thermometer. Microscopically, temperature is a direct measure of the **average translational kinetic energy** of the molecules within a substance.

The formula for kinetic energy is: $\frac{1}{2}mv^2$

Because the mass (m) of the molecules remains constant, any increase in their kinetic energy—and therefore any increase in the temperature—must correspond to an increase in the average velocity (v) of the molecules.

1. The solution is at boiling point: Incorrect. At the boiling point, a substance undergoes a phase change. During an ideal phase change, added heat goes into breaking intermolecular bonds rather than increasing kinetic energy, so the temperature remains constant.

2. The solution is undergoing a phase change: Incorrect, for the exact same reason as above. The problem explicitly states the temperature is *increasing*, which means it is not in the middle of a phase change plateau.

3. The solution's temperature increase is proportional to the Latent Heat Lv : Incorrect. Latent heat is the energy required to change the phase of a substance *without* a change in temperature (using the formula Q=mL). The temperature increase of a solution is dictated by its **specific heat capacity** (c), using the formula Q=mcΔT.

4. All of the above: Incorrect, as the first three statements are false.

5. The velocity of molecules in the solution is increasing: Correct. As the temperature increases, the average kinetic energy of the particles increases, meaning they are moving faster.

Three objects are kept outside for a long time on a cold day: a piece of cotton, a piece of wood and a piece of metal. Which object feels the coldest when you touch it?

A) The cotton **B)** The wood **C)** The metal

D) They all feel the same

Which of the objects above would have the lowest temperature?

A) The cotton **B)** The wood **C)** The metal

D) They are all the same temperature

Three objects are kept outside for a long time on a cold day: a piece of cotton, a piece of wood and a piece of metal. Which object feels the coldest when you touch it?

A) The cotton **B)** The wood **C)** The metal

D) They all feel the same

Which of the objects above would have the lowest temperature?

A) The cotton **B)** The wood **C)** The metal

D) They are all the same temperature

Metal feels colder than wood because it has a higher thermal conductivity, meaning it conducts heat away from your body much faster than wood, making you perceive it as colder even if they are at the same actual temperature.