Temperature

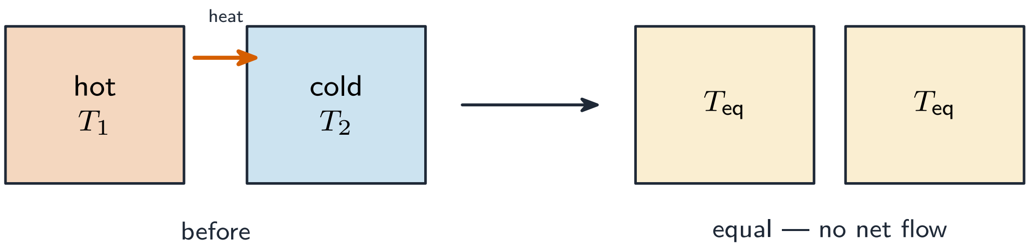
A-Level Physics

Thermal equilibrium

Heat 热量 (thermal energy) flows from a **higher temperature** to a **lower temperature**. When two bodies touch, energy moves until their temperatures are equal — they reach **thermal equilibrium** 热平衡. At equilibrium there is no net flow of energy.

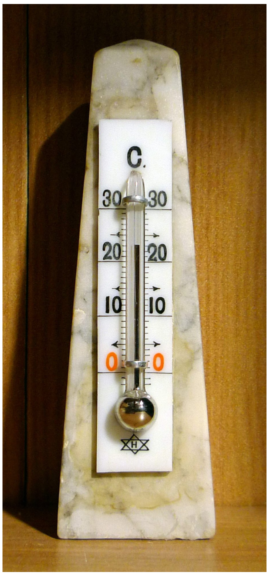
Two regions at the **same temperature** 温度 are in thermal equilibrium with each other — no net energy flows, even though particles still exchange energy.

Temperature decides the **direction** of heat flow. It is not a measure of how much **thermal energy** 热能 a body holds. A small cup of boiling water (100 °C) holds far less energy than a swimming pool at 25 °C, but a piece of metal put in the cup gains energy while one put in the pool loses it.



Heat flows from hot to cold until both reach the same temperature — thermal equilibrium

Measuring temperature

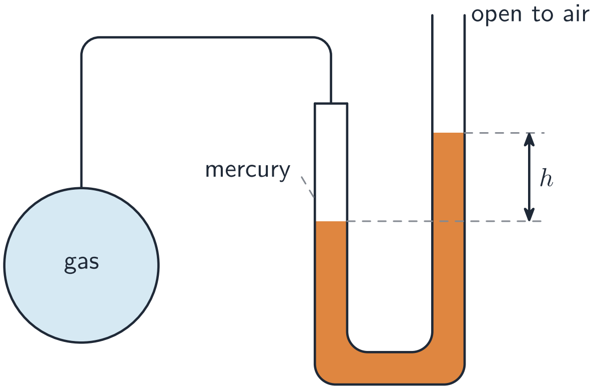


A thermometer measures temperature on a defined scale.

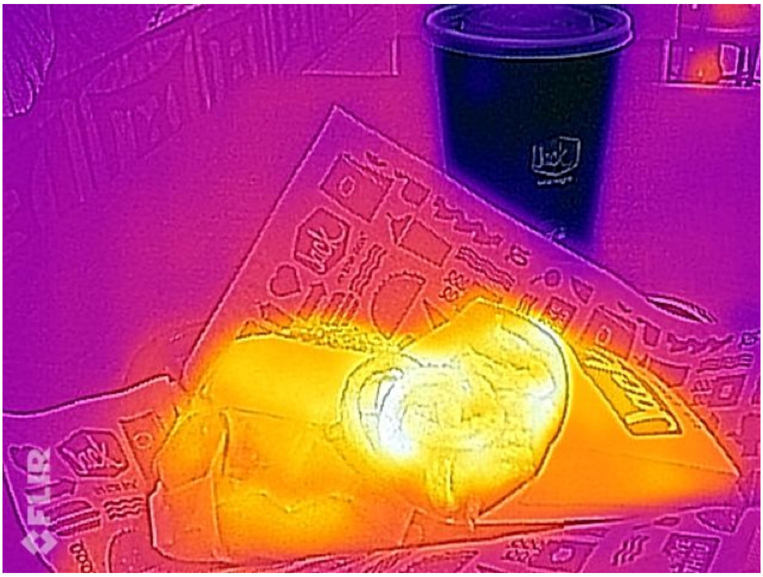
Any physical property that **changes in a repeatable way with temperature** can make a **thermometer** 温度计. Examples:

- **volume of a liquid** — a liquid-in-glass thermometer (mercury or alcohol). As the temperature rises, the liquid expands and rises up a narrow **capillary** 毛细管.
- **volume of a gas at constant pressure** — a gas thermometer. The gas volume rises in step with the absolute temperature.
- **resistance of a metal** — a resistance thermometer. A metal's **resistance** 电阻 rises nearly in step with temperature over a wide range.
- **e.m.f. of a thermocouple** — a **thermocouple** 热电偶 is two different metals joined at two points; the **electromotive force** 电动势 it makes depends on the temperature difference between the joins.

Different thermometers can read slightly differently if the property does not change in a straight line; they agree only at the **calibration** 校准 points.



A constant-volume gas thermometer — the gas pressure is found from the height difference h



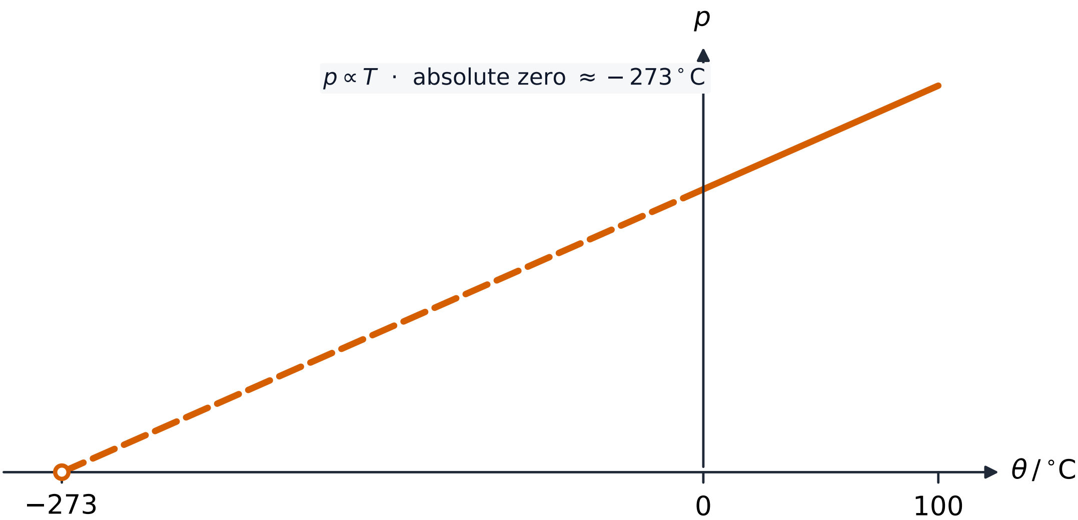
A thermal (infrared) camera maps temperature to colour: the hot fries glow bright orange, the cold drink stays dark

Thermodynamic temperature scale

The **thermodynamic temperature** 热力学温度 (or **absolute temperature** 绝对温度) scale does not depend on any one substance — only on the laws of thermodynamics. Its unit is the **kelvin** 开尔文 (K).

Absolute zero

The lowest possible temperature is **zero kelvin** (0 K), called **absolute zero** 绝对零度. There a system has its least possible **internal energy** 内能 — particles have no random motion to speak of. Nothing can be cooled below this.



Extrapolating the pressure–temperature line back to zero pressure gives absolute zero, about −273 °C

Celsius scale

The **Celsius** 摄氏度 scale θ is shifted from the thermodynamic scale by a fixed amount:

$$T/\mathrm{K} = \theta/{}^\circ\mathrm{C} + 273.15.$$

So 0 °C = 273.15 K and 100 °C = 373.15 K. A kelvin and a degree Celsius are the **same size**, so a temperature **difference** of 1 K equals 1 °C — but the absolute values differ by 273.15.

In gas-law calculations you must always use **absolute** temperatures in kelvin. Using °C gives wrong answers.

Specific heat capacity

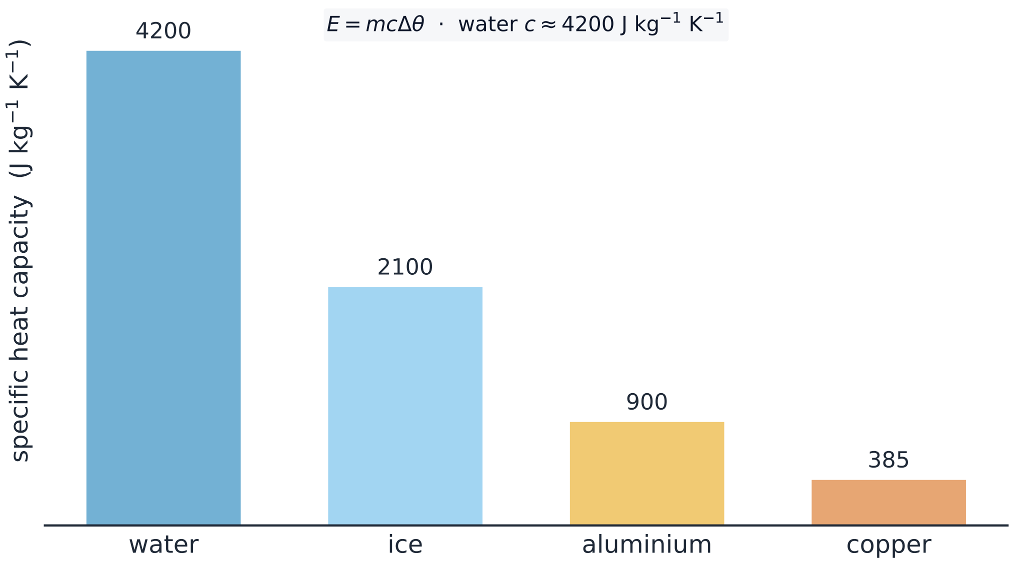
The **specific heat capacity** 比热容 c of a substance is the **energy** 能量 needed to raise the temperature of **unit mass** by **one kelvin**:

$$c = \frac{Q}{m\Delta T} \qquad \Longleftrightarrow \qquad Q = mc\Delta T.$$

Unit: J kg^{-1} K^{-1}.

Examples:

- water: $c \approx 4200$ J kg^{-1} K^{-1} (high — why water is a good coolant and why oceans steady the climate).
- aluminium: $c \approx 900$ J kg^{-1} K^{-1}.
- copper: $c \approx 385$ J kg^{-1} K^{-1}.



Water's specific heat capacity is far higher than common solids — why it is such a good coolant

To find an unknown c by experiment: supply known energy Q electrically ($Q = VIt$, from the **power** 功率), then measure the temperature rise ΔT of a known **mass** 质量 m. Then $c = Q/(m\Delta T)$. Reduce heat loss with **insulation** 隔热 and use a rise of about 10 K (big enough to measure well, small enough to limit losses).

Worked example. How much energy is needed to heat 0.50 kg of water from 20 °C to 100 °C? (Specific heat capacity of water $c = 4200$ J kg^{-1} K^{-1}.)

A temperature difference is the same in K and °C, so $\Delta T = 80$:

$$Q = mc\Delta T = 0.50 \times 4200 \times 80 = 1.68 \times 10^5 \text{ J } (= 168 \text{ kJ}).$$

When two bodies reach thermal equilibrium with no heat lost to the surroundings, the energy gained by the colder one equals the energy lost by the hotter one:

$$m_1 c_1 (T_{\text{eq}} - T_1) = m_2 c_2 (T_2 - T_{\text{eq}}).$$

Worked example. 0.20 kg of water at 80 °C is mixed with 0.30 kg of water at 20 °C, with no heat lost. Find the final temperature.

The heat lost by the hot water equals the heat gained by the cold water (the c of water cancels):

$$0.20\,(80 - T_{\text{eq}}) = 0.30\,(T_{\text{eq}} - 20) \quad \Rightarrow \quad T_{\text{eq}} = 44 \text{ °C}.$$

Specific latent heat

When a substance changes state (solid ↔ liquid, or liquid ↔ gas) at constant temperature, energy must be supplied (or removed) with **no** temperature change. This energy is the **latent heat** 潜热.

The **specific latent heat** 比潜热 L is the energy to change the state of **unit mass** at constant temperature:

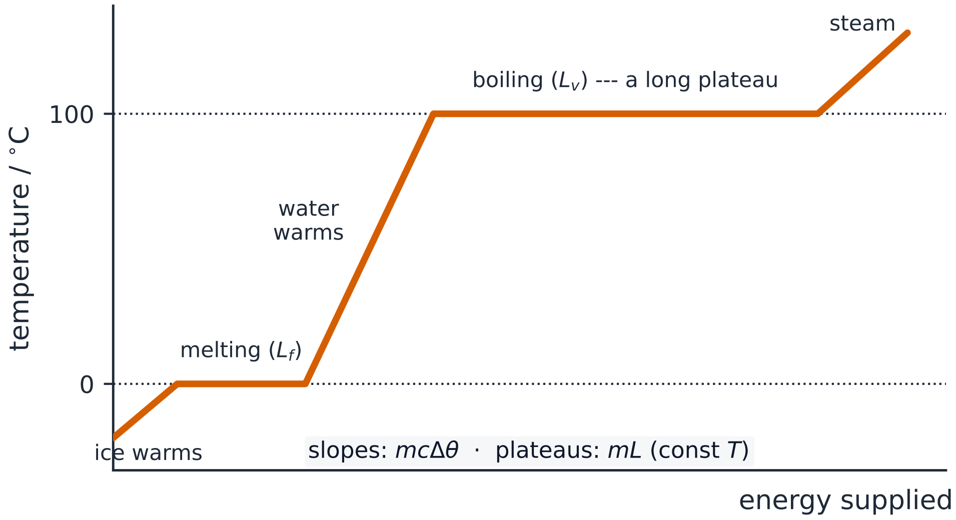
$$L = \frac{Q}{m} \qquad \Longleftrightarrow \qquad Q = mL.$$

Unit: J kg^{-1}.

Two kinds:

- **specific latent heat of fusion** 熔化 L_f — for melting or freezing (solid ↔ liquid).
- **specific latent heat of vaporisation** 汽化 L_v — for boiling or condensing (liquid ↔ gas).

For water at atmospheric pressure: $L_\text{f} \approx 3.34 \times 10^5$ J kg^{-1} (at 0 °C); $L_\text{v} \approx 2.26 \times 10^6$ J kg^{-1} (at 100 °C). So L_v is about 7 times L_f.



Heating curve: the sloped parts warm the substance ($mc\Delta T$); the flat plateaus are the phase changes (mL)

Worked example. A 2.0 kW heater boils water already at 100 °C. How long does it take to turn 0.10 kg of this water into steam? ($L_v = 2.26 \times 10^6$ J kg^{-1}, no heat lost.)

The energy needed is $Q = mL_v = 0.10 \times 2.26 \times 10^6 = 2.26 \times 10^5$ J. From $Q = Pt$,

$$t = \frac{Q}{P} = \frac{2.26 \times 10^5}{2000} \approx 110 \text{ s}.$$

Why $L_v > L_f$

Two reasons, both from the particle picture of matter:

1. **Bonds**: in melting, only some of the **intermolecular** 分子间 bonds break; the particles stay close as a liquid. In boiling, **all** the bonds must break so the particles can separate. Breaking all of them needs more energy.
2. **Work against the atmosphere**: when a liquid turns to gas it expands hugely (vapour has about 10^3 times the liquid's **volume** 体积), so it does work pushing back the surrounding **atmospheric pressure** 大气压强. That work comes from the energy supplied.

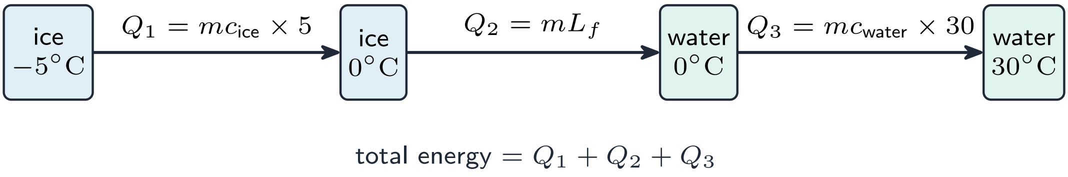
Multi-step problems

If a problem mixes temperature change and a **phase change** 相变 (e.g. ice at −5 °C warming to water at 30 °C):

1. heat the solid from −5 °C to 0 °C: $Q_1 = mc_{ice} \times 5$.

2. melt at 0 °C: $Q_2 = mL_\text{f}$.
3. heat the water from 0 °C to 30 °C: $Q_3 = mc_\text{water} \times 30$.

Total: $Q_1 + Q_2 + Q_3$. A phase change is at constant temperature, so use mL there, not $mc\Delta T$.



Split a mixed problem into stages — warm, change state, warm — then add the energies

When a question gives heater power P and asks for the time, use $Q = Pt$ (assuming no heat loss). Insulating (lagging) the container and using a small mass are common ways to improve the experiment.

Exam tips

- **Thermal equilibrium** means no net heat flow (equal temperature); the thermodynamic scale is fixed by absolute zero and the triple point.
- Convert temperatures with $T/\text{K} = \theta/°\text{C} + 273.15$ and use **kelvin** in energy and gas equations.
- Use $Q = mc\Delta T$ for heating and $Q = mL$ for a change of state (no temperature change) — never mix the two.