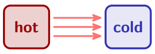
Temperature and Thermal Energy

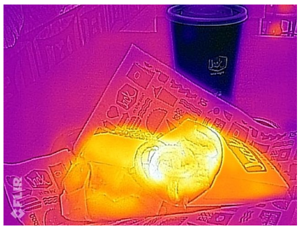
A2 Physics ▪ Topic 14

A-Level Physics



What we will cover

1 Thermal equilibrium
2 Measuring temperature
3 The kelvin & absolute zero
4 Specific heat capacity
5 Specific latent heat
6 Recap

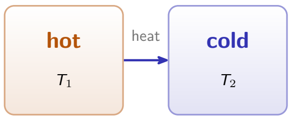


1 Thermal equilibrium

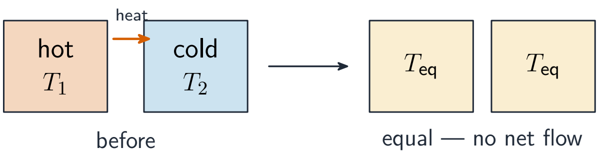
Thermal equilibrium

Two bodies in contact exchange energy until they reach the same **temperature** 温度 – **thermal equilibrium** 热平衡. Heat flows from the hotter to the colder. Once they match, the net flow is zero.

> A thermometer works because it comes to equilibrium with whatever it touches – so it must be small enough not to change that temperature.



What equilibrium means



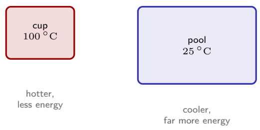
Net energy flows from hot to cold until the two are at the same temperature – that is what a thermometer waits for before it reads.

> At **thermal equilibrium** 热平衡 there is no net flow of energy between the bodies – they are at the same temperature, not necessarily holding the same energy.

Temperature is not energy

Temperature fixes the direction of heat flow. It does not say how much **thermal energy** 热能 a body holds.

> A cup of water at $100\,^{\circ}\mathrm{C}$ holds far less energy than a pool at $25\,^{\circ}\mathrm{C}$ – but metal dropped in the cup gains energy, and in the pool loses it.

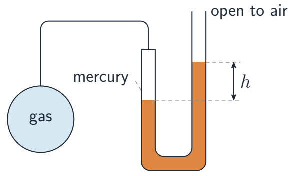


2 Measuring temperature

Making a thermometer

Any property that changes repeatably with temperature will do:

- liquid **density** 密度 – liquid-in-glass
- gas volume (or pressure) – gas thermometer
- **resistance** 电阻 of a metal
- **thermocouple** 热电偶 e.m.f.



> Two thermometers agree only at the calibration points – in between, each follows its own property's curve.

A thermometric property

> Any property that varies reproducibly with temperature will do – here the length of a liquid column.

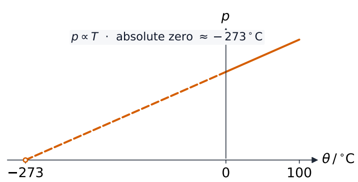
Choosing a thermometric property

what is needed	a property that varies measurably and reproducibly with **thermodynamic temperature** 热力学温度
liquid-in-glass	the length of a mercury or alcohol thread in a **capillary** 毛细管 tube
resistance	the resistance of a wire or a thermistor – non-linear, but very sensitive
a thermocouple 热电偶	two different metals joined at two points; the **electromotive force** 电动势 depends on the temperature difference between the junctions
why a thermocouple	small, fast-responding, and it works over a very wide range
gas thermometer	the pressure of a fixed volume – the most accurate, and the standard the others are calibrated against

> Sensitivity, range and response time are the three criteria. Naming which one your choice wins on is the mark.

3 The kelvin

Absolute zero



The **thermodynamic scale** 热力学温度 leans on no single substance – only on the laws of thermodynamics. Its unit is the **kelvin** 开尔文. At **absolute zero** 绝对零度 ($0\,\mathrm{K}$) a system holds its least possible **internal energy** 内能.

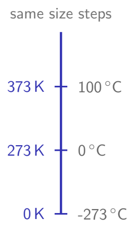
> Cool *any* gas and extrapolate its p–θ line to zero pressure: every gas points at the same $-273\,^\circ\mathrm{C}$.

Kelvin and Celsius

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

- $0\,^\circ\mathrm{C} = 273.15\,\mathrm{K}$; $100\,^\circ\mathrm{C} = 373.15\,\mathrm{K}$
- a kelvin and a degree Celsius are the same size; a kelvin reading is an **absolute temperature** 热力学温度
- so a difference of $1\,\mathrm{K}$ *is* $1\,^\circ\mathrm{C}$

> Gas laws and energy equations need kelvin. Using $^\circ C$ there is simply wrong – but for a ΔT either unit works.



4 Specific heat capacity

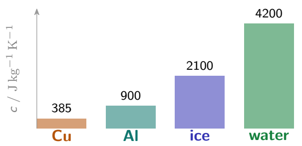
Specific heat capacity

Specific heat capacity 比热容 is the energy to raise unit mass by one kelvin:

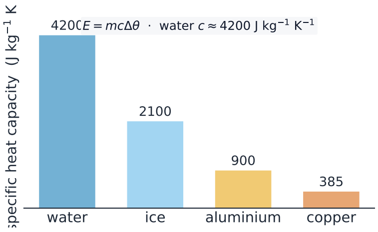
$$c = \frac{Q}{m\Delta T} \iff Q = mc\Delta T$$

$[c] = \mathrm{J\,kg^{-1}\,K^{-1}}$.

> Water's $c \approx 4200$ is far above any solid here – which is why it is such a good coolant, and why the oceans steady the climate.



Water's specific heat capacity is far higher



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

Worked example – heating water

Heat $0.50\,\mathrm{kg}$ of water from 20 to $100\,^\circ\mathrm{C}$. ($c = 4200\,\mathrm{J\,kg^{-1}\,K^{-1}}$)

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

$Q = mc\Delta T = 0.50 \times 4200 \times 80$

$= 1.68 \times 10^5\,\mathrm{J} = 168\,\mathrm{kJ}$

> Do not convert 20 and 100 to kelvin first – the 273.15 cancels in the subtraction. Convert only where an absolute T is needed.

Worked example – mixing

Mix $0.20\,\mathrm{kg}$ of water at $80\,^\circ\mathrm{C}$ with $0.30\,\mathrm{kg}$ at $20\,^\circ\mathrm{C}$, no heat lost. Find the final temperature.

heat lost by the hot = heat gained by the cold (c cancels):

$0.20\,(80 - T_{\mathrm{eq}}) = 0.30\,(T_{\mathrm{eq}} - 20)$

$\Rightarrow T_{\mathrm{eq}} = 44\,^\circ\mathrm{C}$

> Write both sides as a positive energy: (hot $- T_{\mathrm{eq}}$) and ($T_{\mathrm{eq}} -$ cold). The answer sits nearer the bigger mass – here 44, not 50.

5 Specific latent heat

Specific latent heat

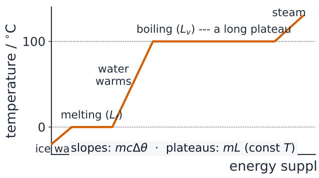
Changing state takes energy at constant temperature – the **latent heat** 潜热:

$$L = \frac{Q}{m} \iff Q = mL, \quad [L] = \mathrm{J\,kg^{-1}}$$

- **specific latent heat of fusion** 熔化潜热 L_f: solid ↔ liquid
- **specific latent heat of vaporisation** 汽化潜热 L_v: liquid ↔ gas

> Sloped = warming ($mc\Delta T$); flat = changing state (mL). Never mix the two.

Specific latent heat, in detail



> Changing state takes energy at constant temperature – the **latent heat** 潜热:
>
> $$L = \frac{Q}{m} \iff Q = mL, \quad [L] = \mathrm{J\,kg^{-1}}$$
>
> .

Why $L_v > L_f$

Bonds
melting breaks *some* bonds – the particles stay close. Boiling breaks *all* of them.

Work on the atmosphere
vapour has $\sim 10^3\times$ the volume, so it pushes the air back as it forms.

> For water $L_v \approx 2.26 \times 10^6$ against $L_f \approx 3.34 \times 10^5\,\mathrm{J\,kg^{-1}}$ – about 7 times larger.

Worked example – boiling with a heater

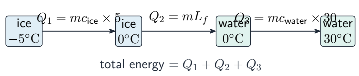
A 2.0 kW heater boils water already at 100 °C. How long to turn 0.10 kg into steam? ($L_v = 2.26 \times 10^6\,\mathrm{J\,kg^{-1}}$)

$$Q = mL_v = 0.10 \times 2.26 \times 10^6 = 2.26 \times 10^5\,\mathrm{J}$$

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

> Already at 100 °C, so there is no $mc\Delta T$ term – all the energy goes into the phase change.

Multi-step problems



Ice at −5 °C → water at 30 °C is three stages:

- $Q_1 = mc_{\text{ice}} \times 5$ – warm the solid
- $Q_2 = mL_f$ – melt at 0 °C
- $Q_3 = mc_{\text{water}} \times 30$ – warm the liquid

> Add $Q_1 + Q_2 + Q_3$. Each phase change is a separate mL step at constant temperature – and the c of ice is not the c of water.

Finding c by experiment, and why boiling costs more

the method	supply known energy electrically: $Q = VIt$, from the **power** 功率 $P = VI$
then	measure the temperature rise and use $Q = mc\Delta\theta$
insulation 隔热	lagging the container reduces heat loss, which is the main source of error
if P is given	use $Q = Pt$ and assume no loss – the question usually says so
why $L_v > L_f$	melting only loosens the **intermolecular** 分子间 bonds; boiling breaks them completely
and	the vapour must also push back the **atmosphere** 大气压 as it expands, and that work is paid for too

Both reasons come from the particle picture. Giving only "the bonds break" misses the expansion work, which is the second marked point.

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.

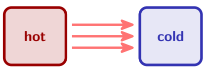
6 Recap

Topic 14 – key takeaways

1. **Equilibrium**
   equal temperature = no *net* heat flow
2. **Kelvin**
   $T/\text{K} = \theta/°\text{C} + 273.15$; use K in gas laws
3. **Heating**
   $Q = mc\Delta T$ – temperature changes
4. **Changing state**
   $Q = mL$ – temperature does *not* change

Check yourself

1. Convert $27\,°\text{C}$ to kelvin.
2. Which equation for melting ice at $0\,°\text{C}$?
3. Why is a flat part of a heating curve flat?
4. Does the hotter body always hold more energy?



Answers **1.** $300.15\,\text{K}$ **2.** $Q = mL_f$ **3.** energy breaks bonds, not raising T **4.** no