

Temperature and Thermal Energy

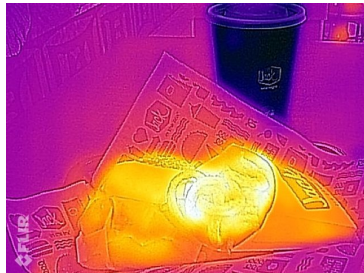
A2 Physics ■ Topic 14

A-Level Physics



What we will cover

- 1 Thermal equilibrium 14.1
- 2 Temperature scales 14.2
- 3 Heat capacity and latent heat 14.3
- 4 Recap



1

Thermal equilibrium

Sheet 14.1 – what you need to know

You must be able to:

- say what **thermal equilibrium** means
- tell temperature apart from internal energy
- share energy between bodies that end at one temperature

What the exam asks

“State what is meant by two objects being in thermal equilibrium.” [2]

“Determine the change in temperature ΔT of Q.” [3]

“Show that the final Celsius temperature θ of the system is given by

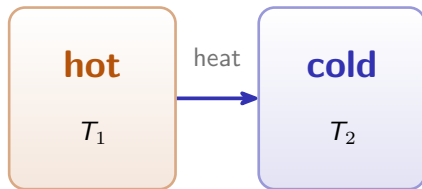
$$\theta = (Mct - XL)/c(M + X).” [2]$$

Practise on exercise sheet 14.1, then try the real exam questions on past-paper sheet 14.1.

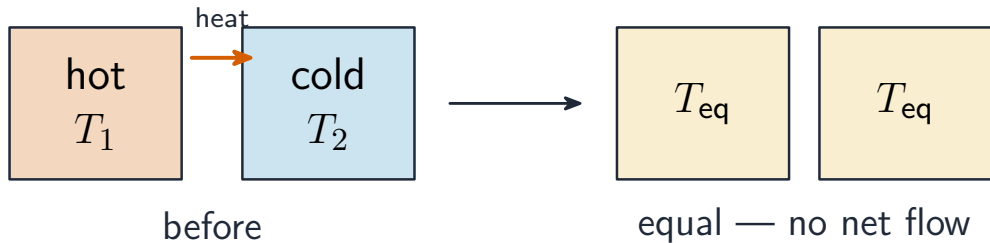
Thermal equilibrium

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°C holds far **less** energy than a pool at 25°C – but metal dropped in the cup **gains** energy, and in the pool **loses** it.



hotter,
less energy



cooler,
far more energy

Sharing energy until equilibrium

“State what is meant by two objects being in thermal equilibrium.” [2]

There is **no net transfer** of thermal energy between them, because they are at the **same temperature**.

Bodies in contact end at **one** temperature: all share the **same** ΔT , container included.

A 0.50 kg copper can ($c = 385$) holds 0.20 kg of water ($c = 4200 \text{ J kg}^{-1} \text{ K}^{-1}$). A heater gives them 12 kJ. Find the temperature rise.

$$E = (m_1 c_1 + m_2 c_2) \Delta T$$
$$\Delta T = \frac{E}{m_1 c_1 + m_2 c_2} = \frac{12\,000 \text{ J}}{(192 + 840) \text{ J K}^{-1}} = 11.6 \text{ K}$$

2

Temperature scales

Sheet 14.2 – what you need to know

You must be able to:

- judge a **thermometric property** by range, sensitivity and response
- state absolute zero ($0\text{ K} = -273.15^\circ\text{C}$) and convert $T/\text{K} = \theta/^\circ\text{C} + 273.15$
- explain why a liquid thermometer does not read thermodynamic temperature

What the exam asks

“State the magnitude and unit of absolute zero on the thermodynamic temperature scale.” [1]

“Explain why a laboratory liquid-in-glass thermometer does not give thermodynamic temperature.” [1]

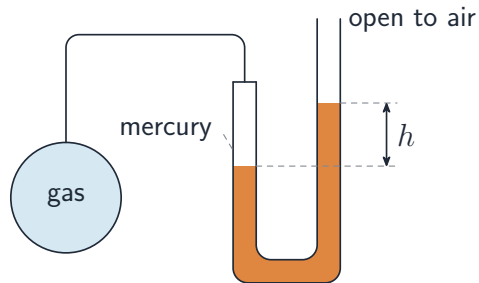
“Suggest a type of thermometer that is suitable for measuring a rapidly changing temperature.” [1]

Making a thermometer

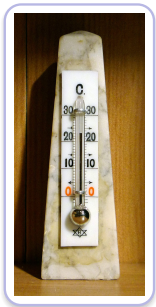
Any property that changes **repeatably** with temperature will do:

- 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



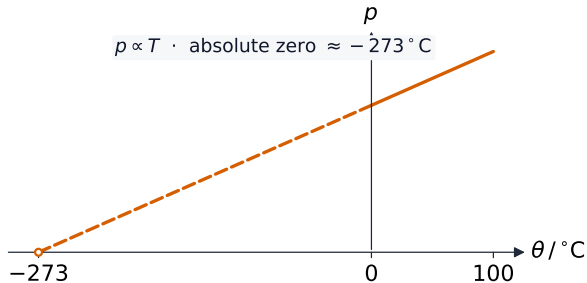
Any property that varies reproducibly with temperature will do – here the length of a liquid column.

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.

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 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°C .

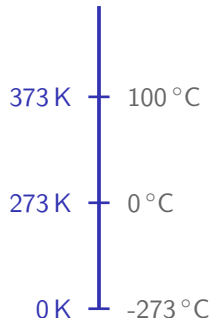
Kelvin and Celsius

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

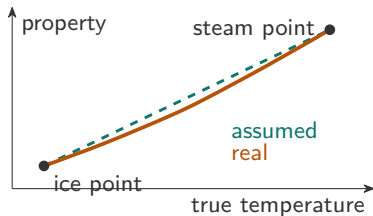
- $0^{\circ}\text{C} = 273.15\text{ K}$; $100^{\circ}\text{C} = 373.15\text{ K}$
- a kelvin and a degree Celsius are the **same size**; a kelvin reading is an **absolute temperature** 热力学温度
- so a **difference** of 1 K is 1°C

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

same size steps



Thermometer answers that score



“Why does a liquid-in-glass thermometer not give thermodynamic temperature?” [1]

Its scale depends on a **property of one substance**, which is not exactly linear; the thermodynamic scale depends on no substance.

“Why is a platinum resistance thermometer unsuitable for a rapidly changing temperature?” [1]

Its **large thermal capacity** makes it respond slowly. A **thermocouple** (tiny junction) responds fast.

“How does a thermistor differ from a platinum wire?” [1]

A thermistor's resistance **falls** as temperature rises, non-linearly; platinum's **rises**, almost linearly.

3

Heat capacity and latent heat

Sheet 14.3 – what you need to know

You must be able to:

- define **specific heat capacity** and **specific latent heat**
- use $E = mc\Delta T$ and $E = mL$, step by step through a change of state
- measure c electrically ($E = VIt$) or by mixtures
- explain why $L_v > L_f$

What the exam asks

“Define specific latent heat.” [2]

“Determine a value, to three significant figures, for the specific latent heat of fusion of water.” [4]

“Explain why, for a substance, the specific latent heat of vaporisation is usually greater than the specific latent heat of fusion.” [3]

Practise on exercise sheet 14.3, then try the real exam questions on past-paper sheet 14.3.

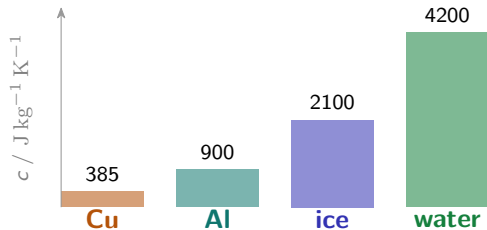
Specific heat capacity

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

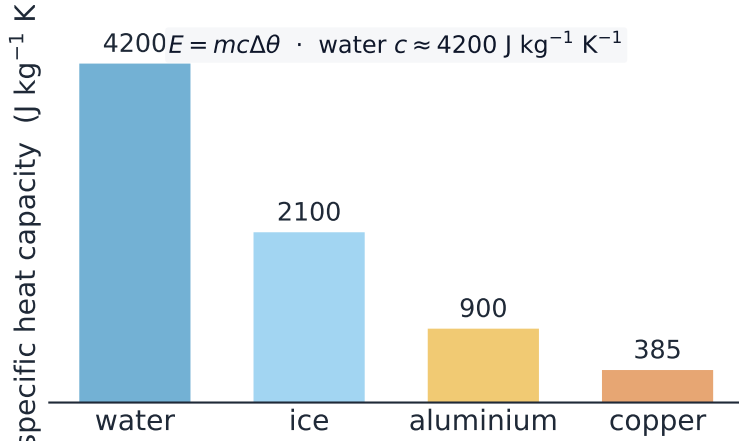
$$c = \frac{Q}{m\Delta T} \iff Q = mc\Delta T$$

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

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 unusually high



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 kg of water from 20 to 100 °C.
($c = 4200 \text{ J kg}^{-1} \text{ K}^{-1}$)

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

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

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 kg of water at 80 °C with 0.30 kg at 20 °C, no heat lost. Find the final temperature.

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

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

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

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

Specific latent heat

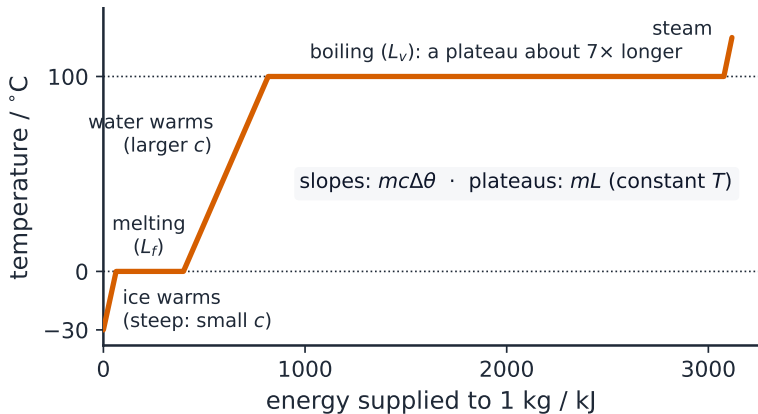
Changing state takes energy at **constant temperature** – the **latent heat** 潜热:

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

- **specific latent heat of fusion** 熔化潜热 L_f : solid $\leftrightarrow$ liquid
- **specific latent heat of vapourisation** 汽化潜热 L_v : liquid $\leftrightarrow$ 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:

$$L = \frac{Q}{m}, \text{ so } Q = mL, \text{ in } \text{J kg}^{-1}.$$

Definitions that score

“Define specific heat capacity.” [2]

The thermal energy needed **per unit mass** to raise the temperature by **one degree** (one kelvin).

$$E = mc\Delta T$$

$$c \text{ in } \text{J kg}^{-1} \text{K}^{-1}$$

“Define specific latent heat.” [2]

The thermal energy needed **per unit mass** to change the state of a substance **without any change of temperature**.

$$E = mL$$

$$L \text{ in } \text{J kg}^{-1}$$

Both marks need both ideas: “per unit mass” **and** “one degree” (or “no change in temperature”).

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 $L_f \approx 3.34 \times 10^5 \text{ J kg}^{-1}$ – about **7 times** larger.

Worked example – boiling with a heater

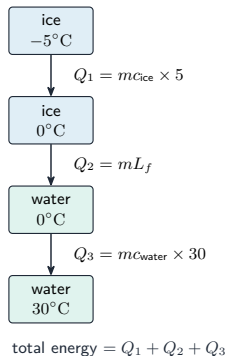
A 2.0 kW heater boils water already at 100 °C. How long to turn 0.10 kg into steam? ($L_v = 2.26 \times 10^6 \text{ J kg}^{-1}$)

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

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

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 $-5^{\circ}\text{C} \rightarrow$ 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.

Ice dropped into warm water

Ice (mass X , at 0°C) into water (mass M , at t). Final temperature θ :

$$E_1 = XL \quad \text{ice melts}$$

$$E_3 = Xc\theta \quad \text{meltwater warms}$$

$$E_2 = Mc(t - \theta) \quad \text{water cools}$$

Energy gained = energy lost:

$$E_1 + E_3 = E_2, \text{ so}$$

$$\theta = \frac{Mct - XL}{c(M + X)}$$

25 g of ice at 0°C goes into 200 g of water at 30.0°C ; it settles at 17.8°C . $c = 4.18 \text{ J g}^{-1} \text{ K}^{-1}$. Find L .

$$E_2 = 200 \text{ g} \times 4.18 \text{ J g}^{-1} \text{ K}^{-1} \times 12.2 \text{ K} = 10\,200 \text{ J}$$

$$E_3 = 25 \text{ g} \times 4.18 \text{ J g}^{-1} \text{ K}^{-1} \times 17.8 \text{ K} = 1860 \text{ J}$$

$$L = \frac{E_2 - E_3}{X} = \frac{10\,200 - 1860}{25} = 334 \text{ J g}^{-1}$$

The meltwater still has to warm from 0°C to θ : leaving out E_3 is the usual lost mark.

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.

4

Recap

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

Topic 14 – key takeaways

1 Equilibrium

equal temperature = no *net* heat flow

2 Kelvin

$T/\text{K} = \theta/^{\circ}\text{C} + 273.15$; use K in gas laws

3 Heating

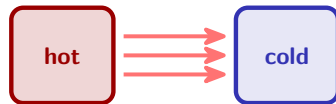
$Q = mc\Delta T$ – temperature changes

4 Changing state

$Q = mL$ – temperature does *not* change

Check yourself

- 1 Convert 27°C to kelvin.
- 2 Which equation for melting ice at 0°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 K 2. $Q = mL_f$ 3. energy breaks bonds, not raising T 4. no