Thermal energy transfers

B.1 · SL and HL

Why does a puddle disappear?

> Matter is particles in constant motion, and energy moves between them.

- A puddle dries long before it could boil.
- A metal bench in the sun feels hotter than a wooden one at the same temperature.
- This unit: particles → temperature → heating → **phase change** → **conduction**, **convection**, radiation.

The molecular model

State	Arrangement	Motion
solid	close; ordered if crystalline	vibrate in place
liquid	irregular, close	vibrate and slide
gas	random, far apart	fast, straight lines

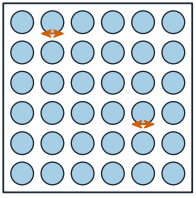
Density

- Aluminium block: 0.54 kg in 2.0×10^{-4} m^3 gives 2700 kg m^{-3}.
- Water 1000 kg m^{-3}; air about 1.2 kg m^{-3}.

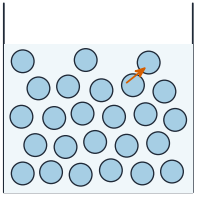
$$\rho = \frac{m}{V}$$

Convert first: 1 cm^3 $= 10^{-6}$ m^3.

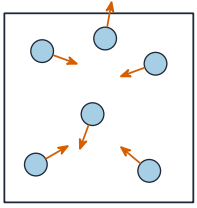
Solid, liquid and gas



solid
fixed positions, vibrate



liquid
close together, slide past



gas
far apart, fast, random

> The spacing explains the densities

Kelvin and Celsius

- 27 °C is 300 K; liquid nitrogen at −196 °C is 77 K.
- A temperature change is the same number in °C and K.

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

Use kelvin in absolute-temperature equations; the examples round the offset to 273.

Temperature measures particle kinetic energy

- At 300 K, $\overline{E}_k = 6.2 \times 10^{-21}$ J.
- Doubling the kelvin temperature doubles $\overline{E}_k$.

$$\overline{E}_k = \tfrac{3}{2} k_B T$$

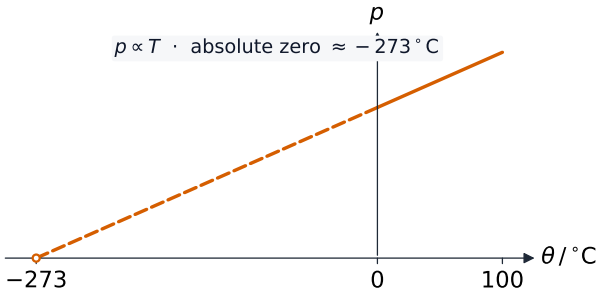
Classical ideal gas: mean translational kinetic energy per particle. $k_B = 1.38 \times 10^{-23}$ J K^{-1}.

Internal energy and thermal equilibrium

- A warm bath has more **internal energy** than a cup of **boiling** water.
- Spontaneous net thermal transfer is hot to cold; equal temperatures give zero net transfer.

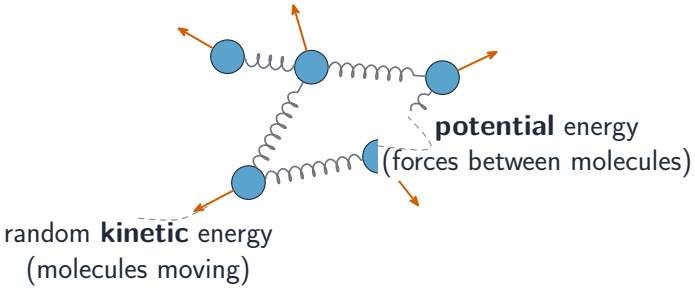
> **Internal energy** total intermolecular potential energy plus total random kinetic energy of the particles

Extrapolating to absolute zero



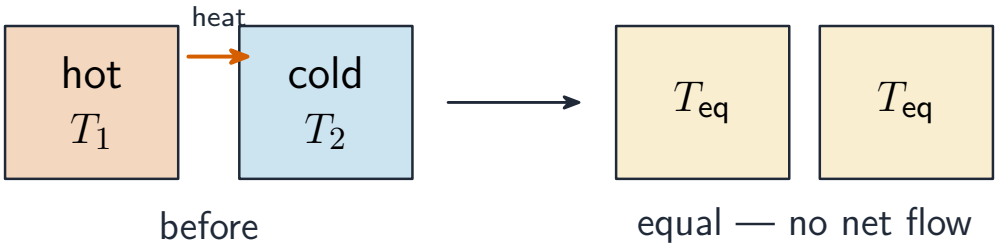
It meets the axis at about -273 °C

Two parts of internal energy



Internal energy is the total of both

Thermal equilibrium



Equal temperature means no net energy flow

Specific heat capacity

- Water 4200 J kg^{-1} K^{-1}; copper 390.
- Kettle: $1.5 \times 4200 \times 80 = 5.0 \times 10^5$ J, about 230 s at 2.2 kW.

$$Q = mc\Delta T$$

Heat losses to the surroundings make a measured c too large.

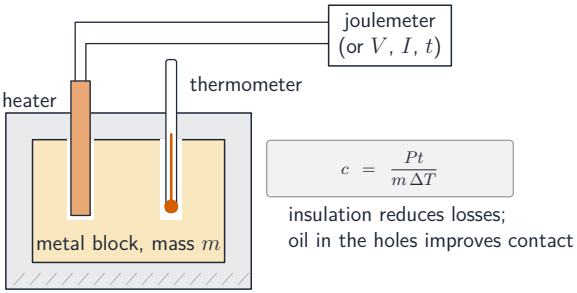
Worked example: copper into water

1. **Given.** 0.20 kg copper at 100°C ($c = 390$) enters 0.30 kg water at 20°C ($c = 4200$), in J/(kg K). Neglect container and losses.
2. **Lost.** $0.20 \times 390 \times (100 - T)$
3. **Gained.** $0.30 \times 4200 \times (T - 20)$
4. **Solve.** $T = 33\,000/1338$

Decision

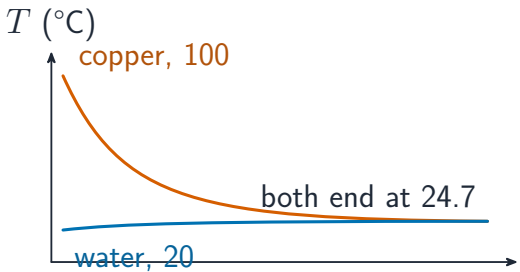
$T = 24.7$ °C; the water barely warms

Measuring specific heat capacity



$c = Pt/(m\Delta T)$

Energy lost equals energy gained



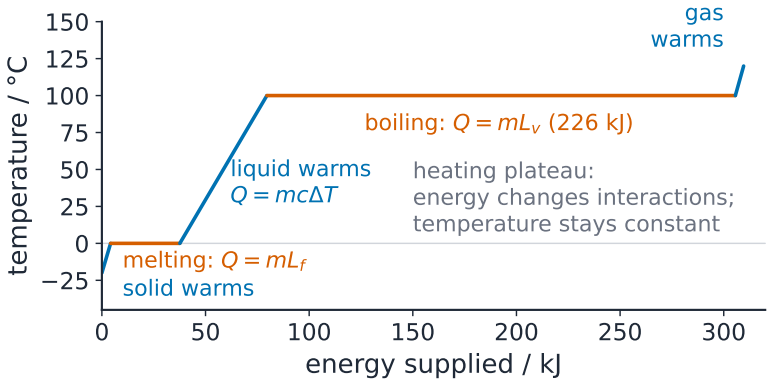
copper loses
$0.20 \times 390 \times 75.3 = 5.9$ kJ

water gains
$0.30 \times 4200 \times 4.7 = 5.9$ kJ

water $mc = 1260$ J/K: 16× copper

Energy lost by one equals energy gained by the other

The heating curve



Melting and **boiling** absorb energy on these ideal constant-pressure plateaus.

Specific latent heat

- Water: $L_f = 3.34 \times 10^5$ J kg^{-1}, $L_v = 2.26 \times 10^6$ J kg^{-1}.
- L_v is larger because the particles are pulled completely apart.

$$Q = mL$$

Positive mL: absorbed in **melting**/vaporization, released in **freezing**/condensation.

Check: ice in a drink

Your turn

An isolated mixture contains 0.050 kg ice at 0 °C and 0.25 kg water at 30 °C. Use water specific heat capacity 4200 J kg^{-1} K^{-1} and fusion latent heat 334000 J kg^{-1}. Neglect the container. What is the final temperature?

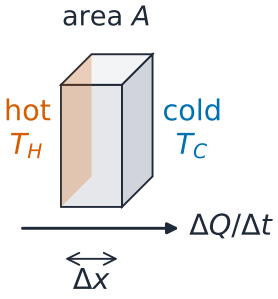
A. 0 °C

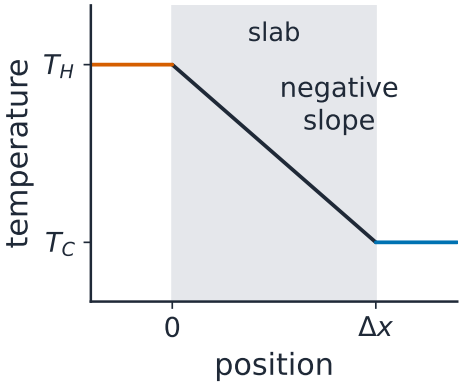
B. 11.7 °C

C. 25 °C

D. 30 °C

Conduction





Microscopic transfers carry energy down the **temperature gradient**.

The rate of conduction

- Glass 4.0 mm thick, 1.5 m^2, 20 K across it gives 6000 W.
- 12 mm of still air with 15 K across it gives only 47 W.

$$\frac{\Delta Q}{\Delta t} = kA\frac{\Delta T}{\Delta x}$$

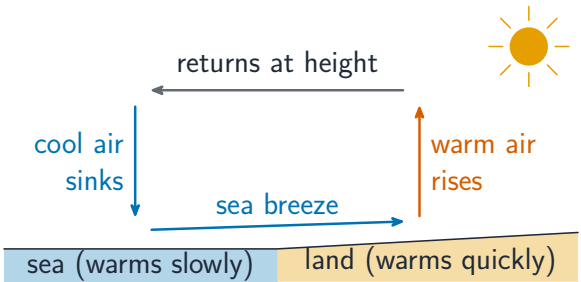
Uniform slab, steady state; $\Delta T = T_H - T_C > 0$ gives the power magnitude.

Convection

Convection moves energy with the fluid itself, so it cannot happen in a solid.

- Warm fluid expands, becomes less dense and rises; cooler fluid sinks.
- Fans or pumps can drive forced convection without buoyant rise.

A sea breeze is convection



The loop closes high up, back towards the sea

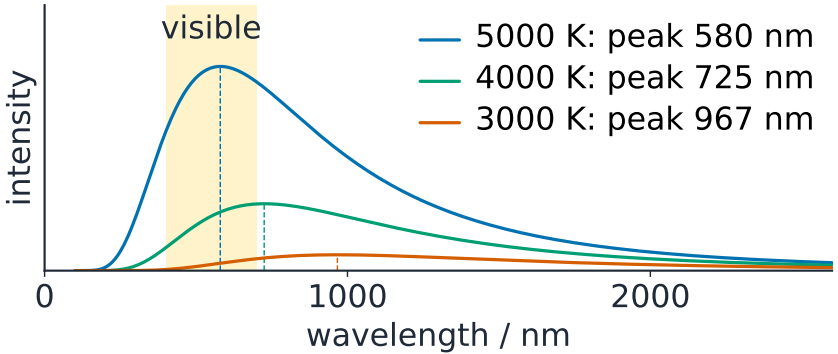
The Stefan–Boltzmann law

- Sun: $R = 6.96 \times 10^8$ m, 5800 K, so $L = 3.9 \times 10^{26}$ W.
- Doubling T multiplies the power by 16.

$$L = \sigma A T^4$$

Black-body emitted power; net radiative loss also subtracts absorbed power.

Black-body spectra



Hotter black bodies emit more and peak at shorter wavelength.

Apparent brightness

- Twice as far away, a quarter as bright.
- The Sun at the Earth: $b = 1.4 \times 10^3$ W m^{-2}.

$$b = \frac{L}{4\pi d^2}$$

Isotropic emission; no intervening absorption; observer far outside the source.

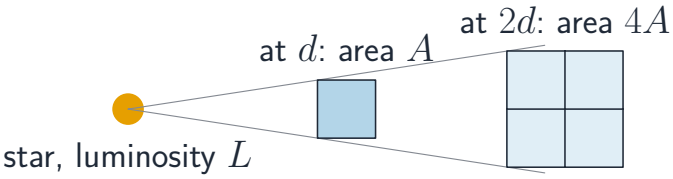
Worked example: a red supergiant

1. **Given.** Spherical black-body model: $T = 3500$ K, $L = 10^5 L_\odot$; reference Sun $T_\odot = 5800$ K.
2. **Ratio.** $R/R_\odot = \sqrt{L/L_\odot}\,(T_\odot/T)^2$
3. **Substitute.** $\sqrt{1.0 \times 10^5} \times (5800/3500)^2$

Decision

$R \approx 870\,R_\odot$

Why brightness falls as $1/d^2$



$b = \frac{L}{4\pi d^2}$: twice as far, a quarter as bright

Double the distance: a quarter of the brightness

Exam tips

> Use kelvin whenever T appears on its own.

- An ideal phase-change plateau has continuing input; a measured plateau alone needs its energy balance checked.
- In mixing problems include a latent step for every **phase change**.
- Compare stars with ratios rather than separate calculations.

Check yourself

Try these

Mix 0.30 kg water at 80°C with 0.20 kg at 20°C. Neglect container and losses. Find the equilibrium temperature.

Copper rod: length 0.50 m, area 1.0×10^{-4} m^2, ends at 100°C and 20°C, $k = 390$ W/(m K). Find steady conduction power.

Find the surface temperature of a star that peaks at 290 nm.