Thermal physics

IGCSE Physics

States of matter 物态

Matter exists in three states: **solid** 固体, **liquid** 液体 and **gas** 气体.

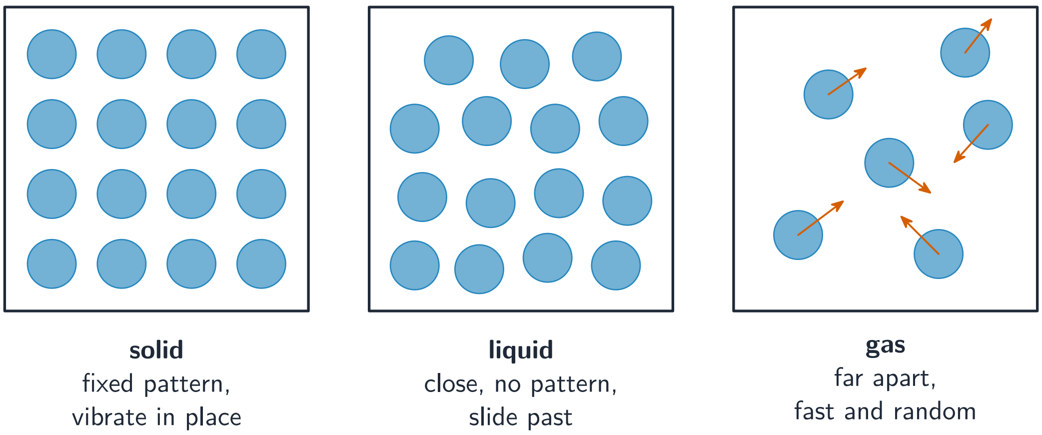
State	Shape	Volume	Particles
Solid	fixed	fixed	close together, in a regular pattern, vibrating
Liquid	takes the shape of the container	fixed	close together, no pattern, can move past each other
Gas	fills the container	changes	far apart, fast, random motion

The changes of state are: melting (solid → liquid), boiling/evaporating (liquid → gas), **condensation** 凝结 (gas → liquid) and **solidification** 凝固 (liquid → solid).

The kinetic particle model 分子动理论

All matter is made of tiny **particles** 粒子 that are always moving. This is the kinetic particle model.

- In a solid the particles only **vibrate** 振动 about fixed positions.
- In a liquid they are still close but can slide past each other.
- In a gas they are far apart and move quickly in random directions.



The same particles in three states: fixed and ordered in a solid, close but disordered in a liquid, far apart and fast in a gas

Temperature and particle energy

When you heat a substance, its particles move faster, so they have more **kinetic energy** 动能. **Temperature** 温度 is a measure of the average kinetic energy of the particles.

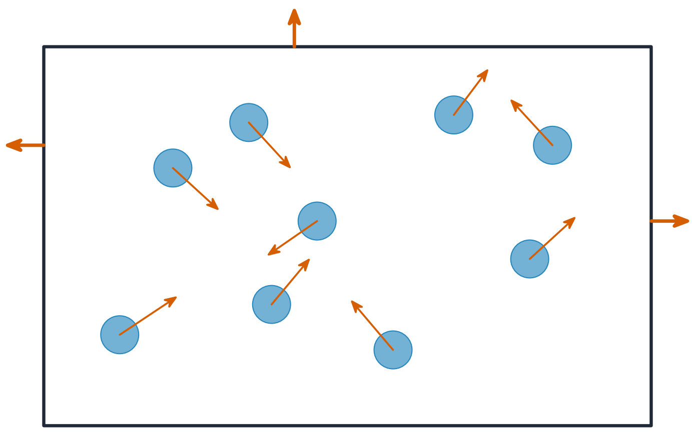
The lowest possible temperature is **absolute zero** 绝对零度, −273 °C. At this point the particles have the least possible energy.

A digital thermometer measures temperature by sensing the kinetic energy of the particles it touches

Image: Vee Gee, Product image (sciencekitstore.com)

Gas pressure

Gas particles hit the walls of their container. Each hit is a tiny push. The **pressure** 压强 of the gas is the total force of these hits per unit area.



gas particles hit the walls — each hit is a tiny force.
Pressure = force per unit area

The gas pressure is the total force of countless particle hits on each unit area of the wall

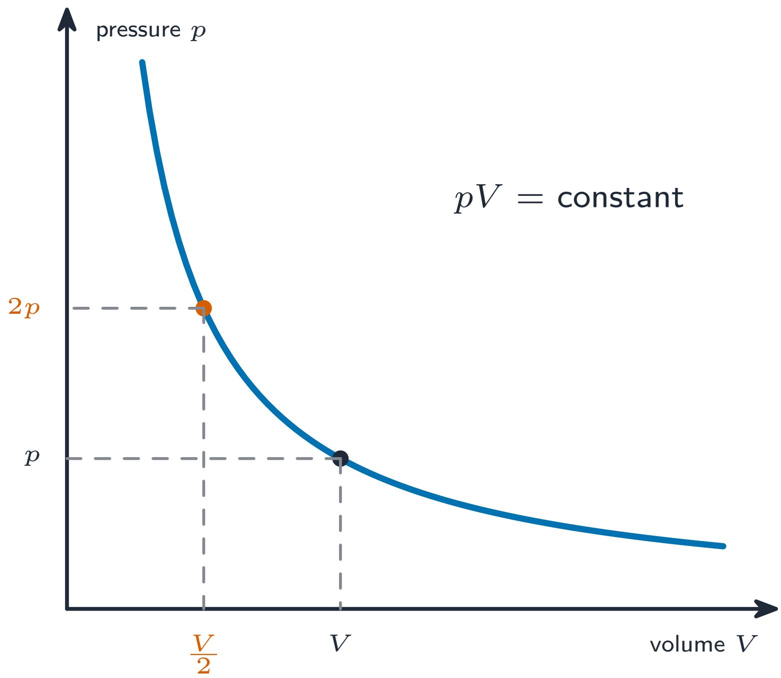
- Heating a gas (at constant volume) makes particles move faster and hit harder and more often, so the pressure rises.

- Squeezing a gas into a smaller volume (at constant temperature) means more hits per second on each unit of area, so the pressure rises.

For a fixed mass of gas at constant temperature:

$$pV = \text{constant}$$

So if the volume halves, the pressure doubles.



At constant temperature the pressure–volume graph is a curve: halve the volume and the pressure doubles, so pV stays constant

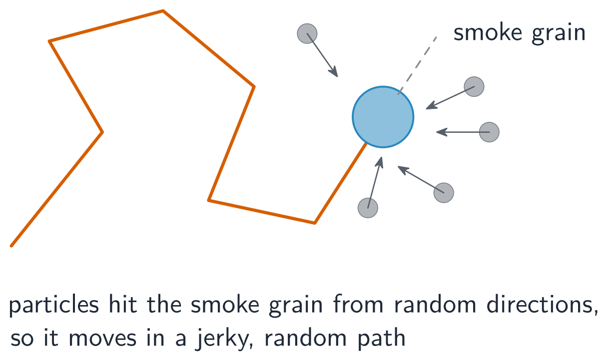
Worked example. A gas has a volume of 200 cm^3 at a pressure of 100 kPa. It is squeezed to 50 cm^3 at constant temperature. Find the new pressure.

Since pV stays constant, $p_1V_1 = p_2V_2$:

$$100 \times 200 = p_2 \times 50 \quad \Rightarrow \quad p_2 = \frac{20\,000}{50} = 400 \text{ kPa}$$

Brownian motion

If you look at smoke in air under a microscope, you see tiny specks moving in a jerky, random way. This is **Brownian motion** 布朗运动. The specks are pushed by fast, invisible air particles hitting them. It is strong evidence for the kinetic particle model.



Random hits from fast air particles push a smoke grain along a jerky, random path

The kelvin scale

Scientists often use the **kelvin** 开尔文 (K) temperature scale, which starts at absolute zero. To convert:

$$T \text{ (in K)} = \theta \text{ (in }^\circ\text{C)} + 273$$

So $0\,^\circ\text{C} = 273$ K.

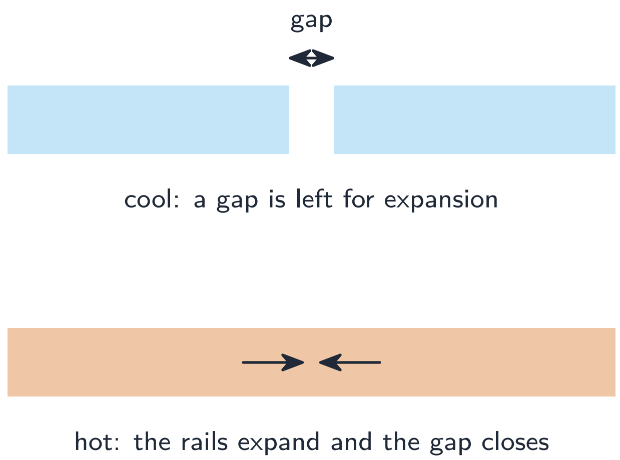
Worked example. Convert $25\,^\circ$C to kelvin, and 200 K to degrees Celsius.

$$25 + 273 = 298 \text{ K}, \qquad 200 - 273 = -73\,^\circ\text{C}$$

Thermal expansion 热膨胀

When matter is heated, its particles move more and take up more space, so the material expands. Gases expand the most, then liquids, then solids.

Everyday examples: gaps are left between railway lines; bridges sit on rollers; a tight metal lid loosens when heated.



A small gap is left between rails when cool, so when they expand in the heat the gap closes instead of buckling the track

Internal energy and specific heat capacity

The **internal energy** 内能 of an object is the total energy of all its particles. Heating an object raises its internal energy and usually its temperature.

The **specific heat capacity** 比热容 is the energy needed to raise the temperature of 1 kg of a material by 1 °C.

$$c = \frac{\Delta E}{m\,\Delta\theta}$$

A material with a high specific heat capacity (like water) needs a lot of energy to warm up and cools down slowly.

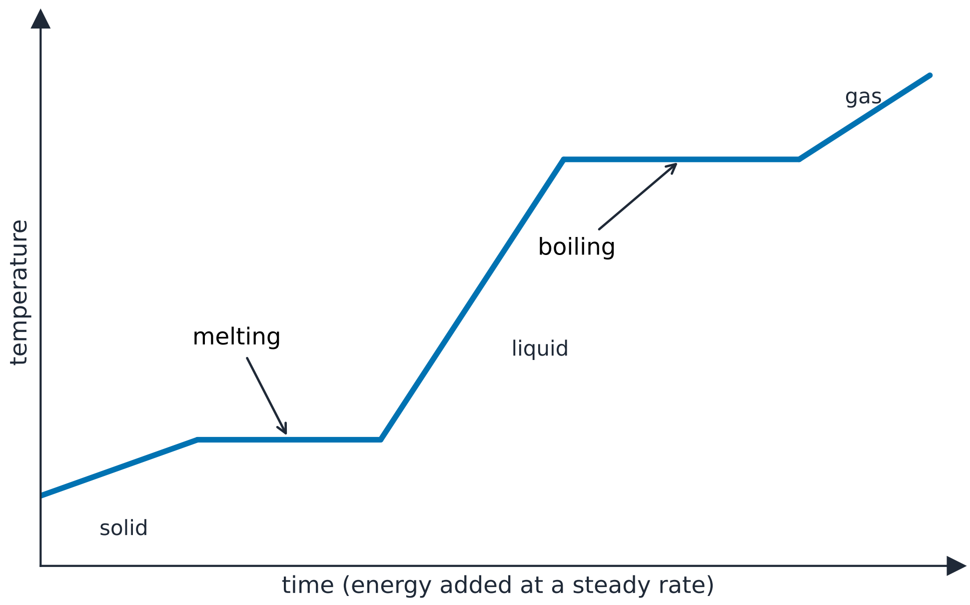
Worked example. How much energy is needed to heat 2.0 kg of water from 20 °C to 70 °C? The specific heat capacity of water is 4200 J/(kg °C).

Rearranging $c = \frac{\Delta E}{m\,\Delta\theta}$ gives $\Delta E = mc\,\Delta\theta$, with $\Delta\theta = 70 - 20 = 50\,°\mathrm{C}$:

$$\Delta E = 2.0 \times 4200 \times 50 = 420\,000\ \mathrm{J} = 420\ \mathrm{kJ}$$

Melting, boiling and evaporation

Melting 熔化 and **boiling** 沸腾 need energy, but the temperature stays the same while the state changes. This energy breaks the forces between particles. For water at normal air pressure, melting is at 0 °C and boiling at 100 °C.



While the substance melts and while it boils the temperature stays flat, even though energy is still being added

Evaporation 蒸发 is when a liquid changes to a gas at its surface, below the boiling point. The fastest particles escape from the surface. Because the fastest (most energetic) particles leave, the average energy of those left behind falls, so the liquid **cools down** 冷却.

Evaporation is faster when the temperature is higher, the surface area is larger, and there is more air movement over the surface.

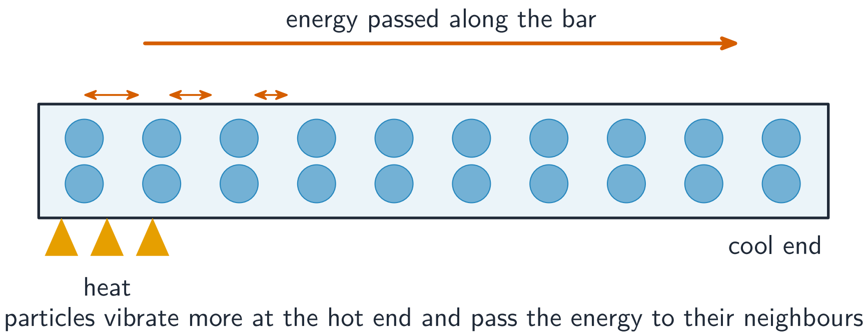
Transfer of thermal energy 热能传递

Thermal energy moves from hotter places to colder places in three ways.

Conduction

Conduction 热传导 is the transfer of thermal energy through a material without the material moving. Heated particles vibrate more and pass the energy to their neighbours. In metals, free (**delocalised**) **electrons** 自由电子 carry energy quickly, so metals are good **thermal conductors** 热导体.

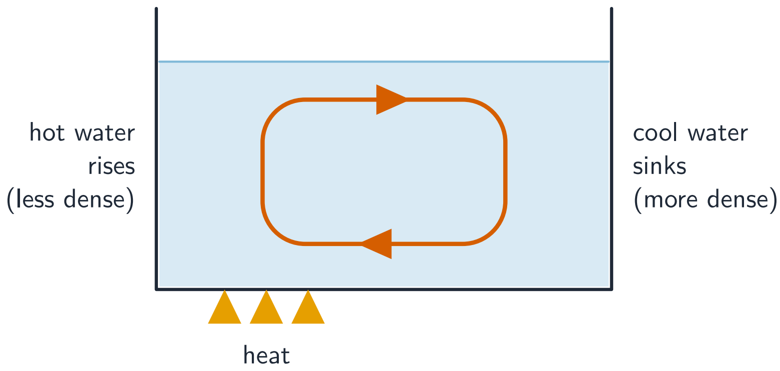
Materials that conduct badly (like air, wood and plastic) are **thermal insulators** 热绝缘体.



In conduction the vibrating particles pass energy to their neighbours, so energy flows from the hot end to the cool end

Convection

Convection 对流 happens in liquids and gases. When a fluid is heated it expands, becomes less dense, and rises. Cooler, denser fluid sinks to take its place. This circle of moving fluid is a **convection current**.



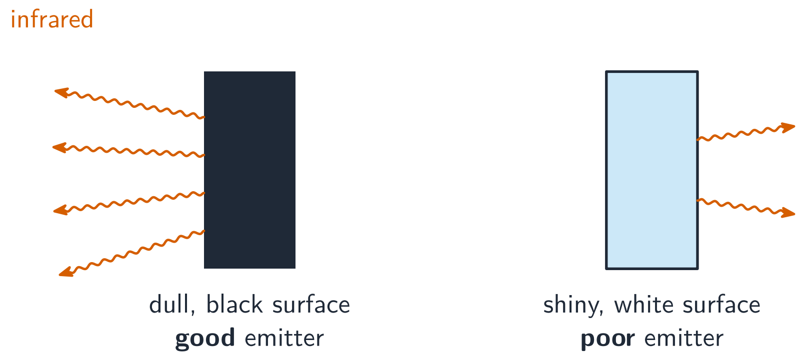
Heated fluid rises and cooler fluid sinks, setting up a convection current

Convection cannot happen in a solid because the particles cannot move from place to place.

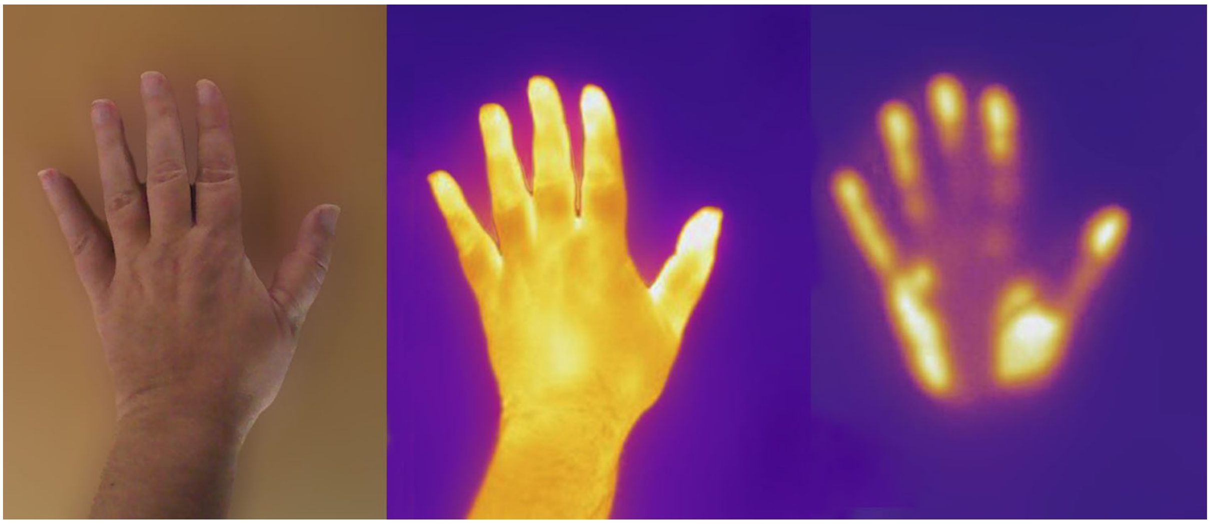
Radiation

Thermal radiation 热辐射 is energy carried by **infrared** 红外线 waves. All objects emit it, and it needs no material to travel through —it can cross empty space (this is how energy reaches us from the Sun).

A surface that is **dull** 暗淡 and black is a good **emitter** 发射体 and a good **absorber** 吸收体 of infrared. A surface that is shiny and white is a poor emitter and a good **reflector** 反射体.



A dull black surface emits (and absorbs) infrared much better than a shiny, white one



A thermal (infrared) camera turns the infrared given off by a warm hand into a picture; brighter means hotter

An object stays at a constant temperature when it emits energy at the same rate as it absorbs energy. The rate of emission is greater when the surface is hotter and larger. The **Earth** works this way: it holds a steady temperature when the energy it radiates back into space balances the energy it receives from the Sun. Upset that balance –more energy absorbed, or less radiated away because greenhouse gases trap outgoing infrared –and the Earth's surface warms until a new balance is reached.

Exam tips

- In the **kinetic particle model**, heating a gas makes its particles move faster and hit the walls harder and more often, so the pressure rises. The particles themselves do not get bigger.
- **Evaporation** happens only at the surface and at any temperature; **boiling** happens throughout the liquid at one fixed temperature. Evaporation cools the liquid left behind, because the fastest particles escape.

- During **melting** and **boiling** the temperature stays constant even though energy is still being supplied —that energy breaks the forces between particles.
- For **specific heat capacity** use $\Delta E = mc\,\Delta\theta$, where $\Delta\theta$ is the *change* in temperature, not the final temperature.
- Dull black surfaces are the best **emitters and absorbers** of infrared; shiny, light surfaces are the best reflectors. **Convection** needs a fluid to flow, so it cannot happen in a solid.