Thermal physics

IGCSE Physics

States of matter 物态

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

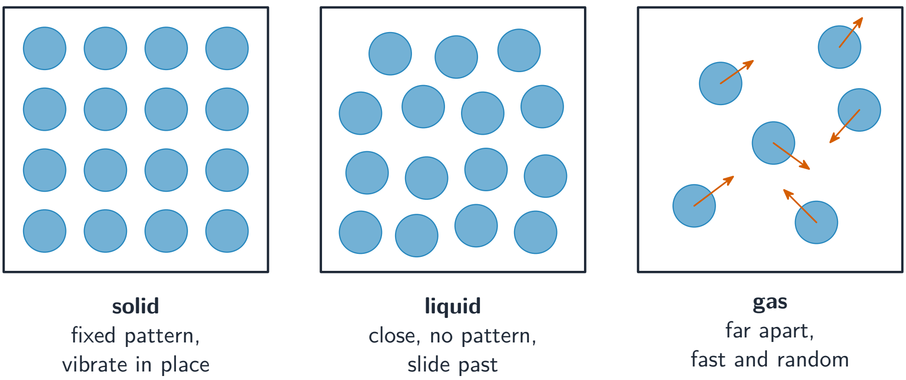
State	Shape	Volume	Particles
Solid	fixed	fixed	close together, in a regular pattern, vibrating
Liquid	takes the shape of the container	fixed	close together, no pattern, can move past each other
Gas	fills the container	changes	far apart, fast, random motion

The changes of state are: melting (solid → liquid), boiling/evaporating (liquid → gas), **condensation** 凝结 (gas → liquid) and **solidification** 凝固 (liquid → solid). In condensation the gas particles slow down and come close together to form a liquid. In solidification the liquid particles lose energy and settle into fixed positions.

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

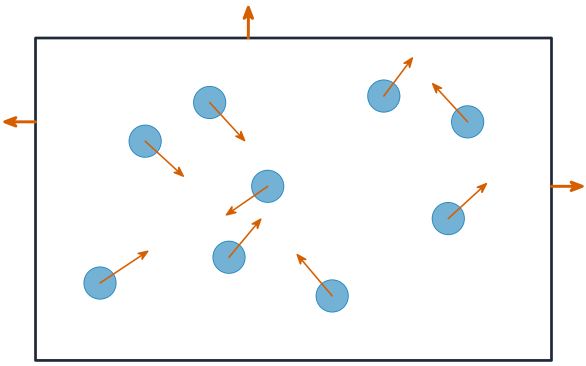
When you heat a substance, its particles move faster, so they have more **kinetic energy** 动能. **Temperature** 温度 is a measure of the average kinetic energy of the particles.

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

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

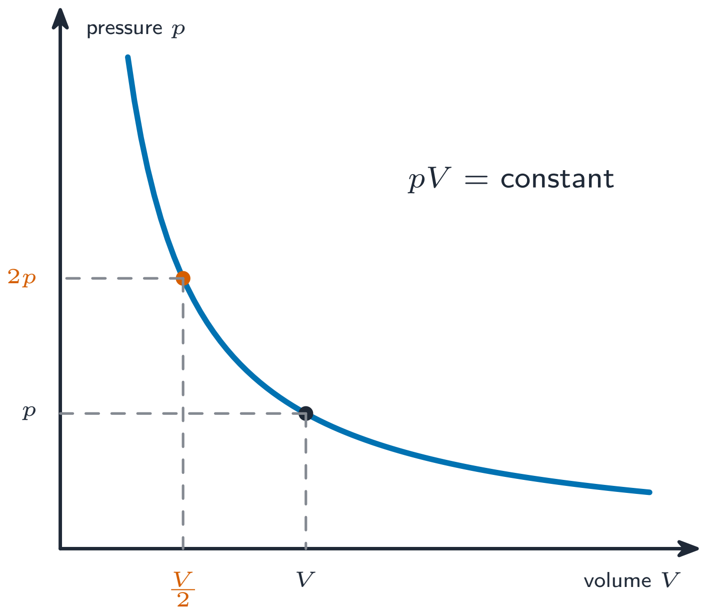
The gas pressure is the total force of countless particle hits on each unit area of the wall

- 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

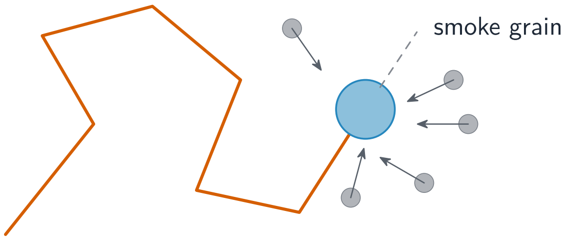
Worked example. A gas has a volume of 200 cm^3 at a pressure of 100 kPa. It is squeezed to 50 cm^3 at constant temperature. Find the new pressure.

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.

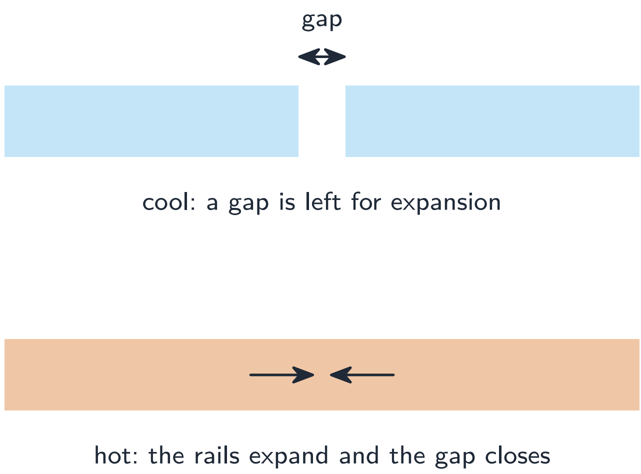
Worked example. Convert $25\,^\circ\text{C}$ to kelvin, and 200 K to degrees Celsius.

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

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. This order comes from the forces between the particles: in a solid the particles are held tightly in a **lattice** 晶格 (a fixed pattern), so they can only vibrate a little more; in a liquid they are held less strongly; in a gas the forces are very weak, so the particles spread out much more.

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 $\Delta\theta = 70 - 20 = 50\,°\mathrm{C}$:

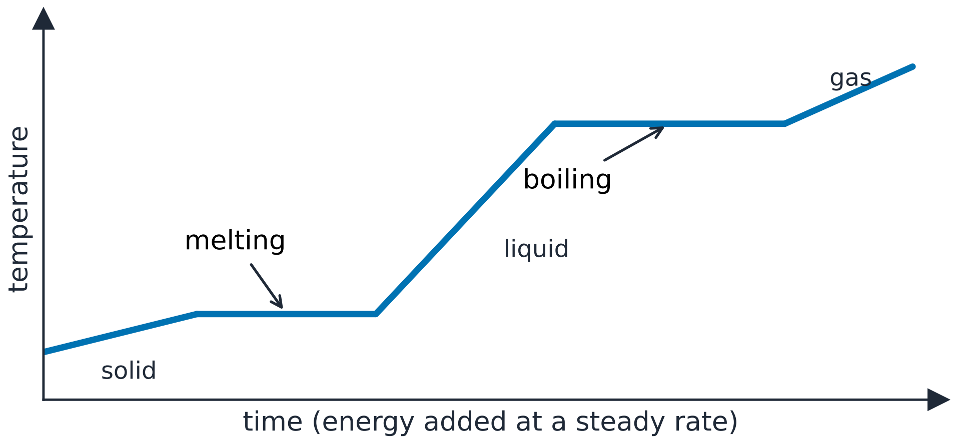
$$\Delta E = 2.0 \times 4200 \times 50 = 420\,000 \text{ J} = 420 \text{ kJ}$$

Measuring specific heat capacity. For a solid, use a metal block with two holes: one for an electric **heater** 加热器 and one for a **thermometer** 温度计. Measure the mass m of the block. Switch on the heater for a measured time t and record the current I and the voltage V, so the energy supplied is $E = IVt$ (or read the energy from a joulemeter). Record the temperature rise $\Delta\theta$. Then $c = \dfrac{E}{m\,\Delta\theta}$. For a liquid, heat a measured mass of the liquid in a container and stir it, so the temperature is the same all through. Wrap the block or the container in **insulating material** 隔热材料, so less energy escapes to the air.

Boiling water: internal energy rises with temperature; specific heat capacity is energy per kg per °C

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.



plateau: latent heat changes state at constant temperature

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. An object touching an evaporating liquid also cools, because the liquid takes energy from it: this is why sweat cools your skin.

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.

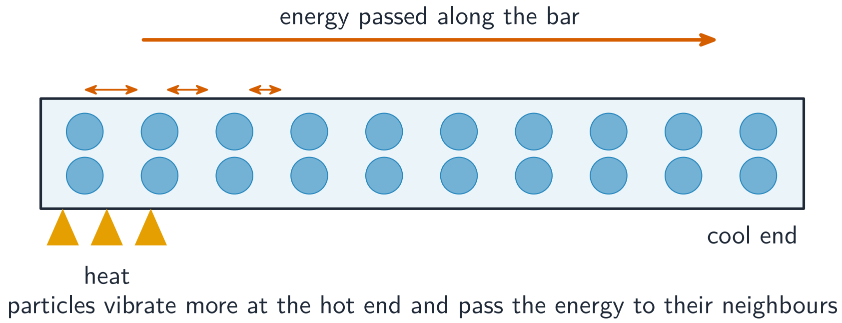
Conduction

Conduction 热传导 is the transfer of thermal energy through a material without the material moving. The particles in a solid sit in a lattice. Heated particles vibrate more and pass the energy to their neighbours. In metals, free electrons (**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.

Testing conductors. Fix a drawing pin with a little wax to one end of rods of copper, iron, glass and wood, and heat the other ends equally. The pin drops first from the copper rod, then from the iron rod, and last (or never) from the glass and the wood: metals are the best conductors. A metal rod held in a flame soon feels hot; a wooden rod does not.

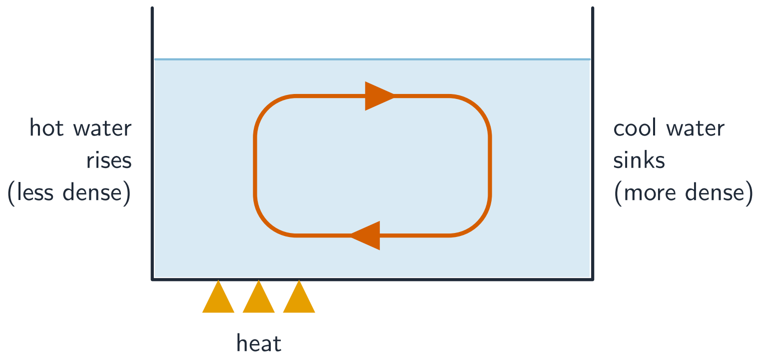
Gases and most liquids are bad conductors because their particles are far apart and only pass on energy when they happen to collide. There is no lattice and there are no free electrons.



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

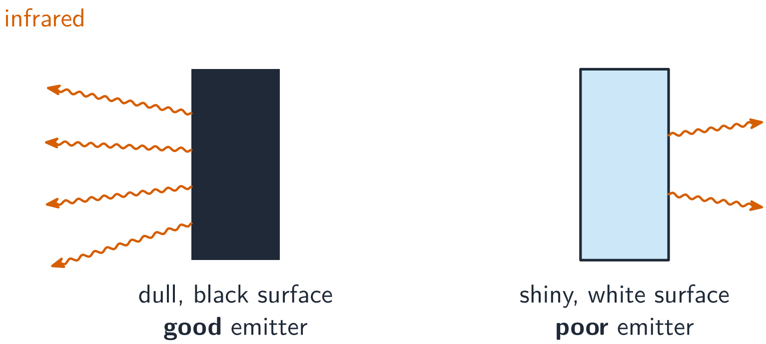
Showing convection. Drop a crystal of purple **potassium permanganate** 高锰酸钾 into a beaker of water and heat the beaker gently under the crystal. A coloured stream rises above the heat, spreads across the top and sinks at the sides. In air, a lit candle under one chimney of a smoke box pulls smoke down the other chimney and up above the flame.

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

Radiation

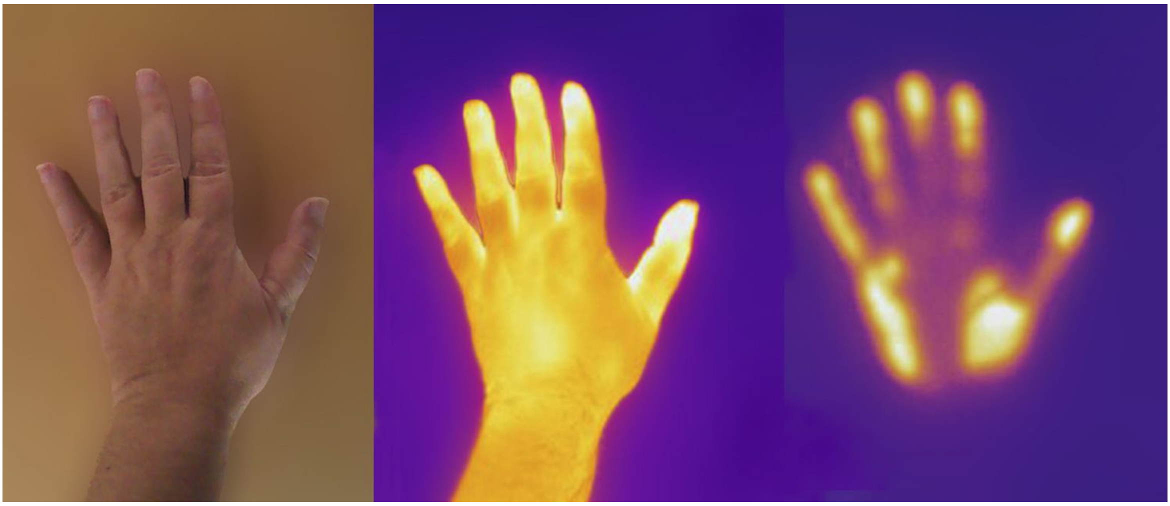
Thermal radiation 热辐射 is energy carried by **infrared** 红外线 waves. All objects emit it, and it needs no material to travel through — it can cross empty space (this is how energy reaches us from the Sun).

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

Comparing surfaces. Fill two cans, one dull black and one shiny silver, with hot water at the same temperature, and put a thermometer in each. The black can cools faster, so it is the better emitter. Then put the same two cans, full of cold water, at equal distances from a heater. The black can warms faster, so it is the better absorber. A **Leslie cube** 莱斯利立方体 (a metal box with one side of each finish) shows the same thing.



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. If an object absorbs energy faster than it emits it, its temperature rises; if it emits faster than it absorbs, its temperature falls.

The Earth's temperature. The Earth absorbs radiation from the Sun and emits infrared radiation back into space. Its average temperature stays constant only when the two rates are equal. Anything that changes this balance changes the temperature. Gases in the **atmosphere** 大气 such as carbon dioxide absorb some of the emitted infrared and send part of it back down, so more of these gases warms the Earth. Clouds and ice reflect incoming sunlight, so less ice means more energy is absorbed, and the Earth warms further.

Everyday examples

- A kitchen pan has a metal base that conducts energy quickly to the food, and a plastic or wooden handle that is an insulator, so you can hold it.
- A **radiator** 散热器 heats a room by convection: the air next to it warms, rises, and cooler air flows in to take its place, so the whole room warms.
- Sitting near a fire you feel its radiation on your face at once; the air between you and the fire is a poor conductor.
- A **vacuum flask** 保温瓶 keeps a drink hot by stopping all three transfers: the vacuum between its double walls stops conduction and convection, and its shiny silver surfaces stop radiation.

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.