

How does thermal energy travel?

Conduction, convection and radiation

Physics · 3A · 12 October 2026

A question from the sea

(slide 2)

The sea is at 20°C . The air is at 20°C . A thermometer in the water and one in the air read the same. You step in: in the water you feel cold, in the air you do not.

Before moving on. Why? Three possible answers. (a) The water really is colder than the air. (b) They have the same temperature, but the water takes energy from the skin faster. (c) It is only an impression, in our head. Pick one and keep it: the question stays open until the end of the chapter.

To answer we need three words that are easy to mix up, and three mechanisms of transfer. Let us start with the words.

Three words that are easy to mix up

(slide 3)

Quantity	What it is	Unit
Temperature T	A property of an object, linked to the average kinetic energy of its particles.	K, $^{\circ}\text{C}$
Internal energy	The total energy, kinetic and potential, of all its particles: it is stored in the object.	J
Thermal energy transfer, Q (heat)	Energy that moves from a hotter place to a colder place because of a temperature difference . It is a process , not something an object possesses.	J

An analogy with a bank account. Internal energy is the balance; thermal energy transfer is the payment. After a payment there is no item called “payment” sitting in the account: there is a balance that has changed. In the same way an object does not *contain* heat: it contains internal energy, and when there is a temperature difference some of that energy passes from one object to another. That passage is the heat.

Two consequences. First: two objects at the same temperature can have very different internal energies, because internal energy also depends on the mass and on the substance (a lake and a cup of water at 20°C). Second: temperature tells you in which *direction* energy moves (from hotter to colder), not *how much*.

In the coursebook you will find both *heat* and *thermal energy transfer*. We will use the second when it matters, because it reminds us that it is a transfer.

Three ways to transfer thermal energy

(slide 4)

The coursebook (P3.04) distinguishes three mechanisms.

- **Conduction:** through a material, from particle to particle, without the material moving.
- **Convection:** through a fluid, carried by the movement of the fluid itself.
- **Radiation:** by infrared waves, with no material needed at all.

All three need a temperature difference, and in all three the net direction is from hotter to colder. We take them one at a time, and for each one we use an animation.

Conduction: the metal cube

(slide 5)

On 8 September we touched four cubes: glass, metal, wood, plastic. All at room temperature, all reading the same on a thermometer. The metal cube felt the coldest.

Before moving on. If the thermometers read the same, what is the finger really detecting?

What is conduction?

(slide 6)

Thermal conduction is the transfer of thermal energy through a material, from the hotter part to the colder part, without the material moving.

A material that passes energy on well is a **thermal conductor**: metals. One that passes on very little is a **thermal insulator**: wood, plastic, air. It always needs a temperature difference: energy flows from high T to low T .

How to read the animation: conduction

(slide 7–8)

The animation shows a rod heated at one end (figure 1). There are two ways to look at it.

View “one rod: atoms and electrons”. There are three thermometers, A, B and C, at 24 %, 52 % and 81 % of the length. Two sliders: the *heater temperature* (I start at 400 °C) and the *material*, from “wood-like” (insulator) to “copper-like” (metal).

What I change. With the material set to insulator, I let the animation run. Then I restart it with the slider halfway and finally all the way to metal. I also try changing the temperature.

What I observe. The atoms do not travel: they vibrate about their position, and the vibration is larger (and the colour warmer) near the heater. Thermometers A, B and C rise one after the other: the energy travels along the rod. Below, a graph $T(t)$ and a readout of how many seconds each point needs to reach 30 °C. As I move the slider towards metal, **free electrons** appear: bright dots running through the lattice. The brightness of an electron shows its kinetic energy; a flash marks a collision with an atom (white flash: the atom gains energy; orange flash:

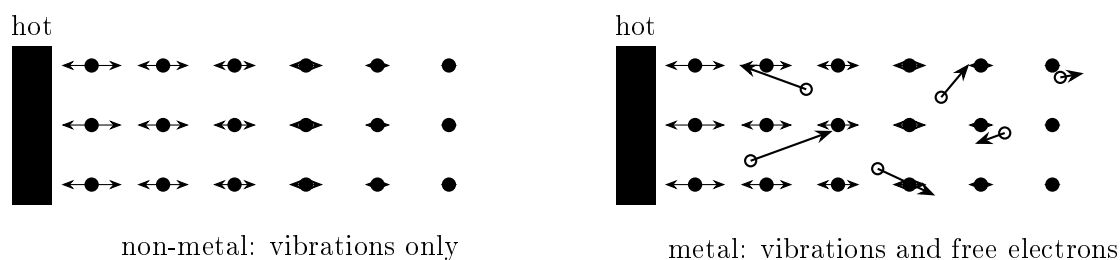


Figure 1: A rod heated at the left. The solid dots are atoms, which vibrate about their position (the double arrow is the size of the vibration, larger at the hot end). The small circles are the free electrons of the metal; the length of the arrow shows the kinetic energy (sketch, not to scale).

it loses energy). Fast electrons come from the hot end, and by colliding with cooler atoms they give them energy even far from the heater.

What it tells us. That the energy crosses the rod and the material does not: the atoms stay where they are. And that in metals there are extra carriers of energy, the electrons, which really move and cover the distance with a few collisions instead of a chain of nudges between neighbours. More metal, faster journey.

View “race: wood – steel – copper”. Three rods heated in the same way. Under each there is a paper clip stuck on with petroleum jelly. When point C reaches 30°C the jelly melts and the clip falls; the animation writes the time of the fall. It is the coursebook’s method (Figure P3.25) for comparing conductors.

Material	wood	glass	steel	copper
Time (s) for C to reach 30°C	28.7	19	8.4	3.5

These are the model’s times, with the heater at 400°C . The scale is compressed: between copper and wood the animation shows a ratio of about 8, whereas in reality wood is far slower. It serves to see the effect, not to measure it.

A note on the coursebook. Describing the paper-clip experiment the coursebook writes that “*heat will quickly reach the petroleum jelly*”. Heat is not a thing that travels: what passes along the rod is *thermal energy*, transferred by conduction. That is why, as in the table of the three words, it is better to say *thermal energy transfer*.

Why metals conduct well

(slide 9)

In a **non-metal** energy passes only by vibrations: the hot end vibrates more, the atoms collide with their neighbours and share energy, atom after atom. It is a slow process.

In a **metal** (Supplement) there is also a cloud of **delocalised (mobile) electrons**, free to move through the metal. Fast electrons from the hot end collide with cooler atoms and give them energy: fast, and also over a long distance.

It is no accident that good electrical conductors (copper, silver) are also good thermal conductors: the same free electrons do both jobs. The quantitative link between the two conductivities is the Wiedemann–Franz law, only qualitative here.

A note on the coursebook. The coursebook says that the electrons “*get hot and move through the metal*”. An electron does not have a temperature: temperature is a property of a collection of particles (*average* kinetic energy). An electron carries kinetic energy and, colliding with a cooler atom, gives part of it away. Also, the coursebook presents vibrations as the mechanism of “poor conductors” only: in fact vibrations occur in every solid, metals included, and in a metal they add to the contribution of the electrons (which in good metals is the dominant one).

How good a conductor is it?

(slide 10)

To compare materials with a number we use the **thermal conductivity** κ (beyond the 0653 syllabus; we mention it because it clarifies what “conducts better” means). If a slab of thickness d and area A has a temperature difference ΔT between its faces, the energy passing through it in a time t is

$$\frac{Q}{t} = \kappa \frac{A \Delta T}{d}, \quad \text{so} \quad \kappa = \frac{Q}{t} \frac{d}{A \Delta T},$$

with κ in $\text{W m}^{-1} \text{K}^{-1}$.

Material	κ ($\text{W m}^{-1} \text{K}^{-1}$)	compared with air
Copper	≈ 400	$\approx 15\,000\times$
Steel	15–50	$\approx 600\text{--}2000\times$
Glass	≈ 1	$\approx 40\times$
Water	≈ 0.6	$\approx 23\times$
Wood	≈ 0.15	$\approx 6\times$
Air	≈ 0.026	1

Typical values near room temperature. The ratio with air is obtained by dividing: for water, $0.6/0.026 \approx 23$; for copper, $400/0.026 \approx 15\,400$.

What the finger feels

(slide 11)

Back to the cubes. The finger does not measure the temperature of the cube: the temperature-sensitive nerves respond to **how fast the finger loses energy**. A metal, a good conductor, carries energy away from the point of contact and spreads it through the rest of the block: the touched region stays cold and the finger keeps giving up energy at a high rate. In wood, an insulator, the surface in contact warms almost immediately to the temperature of the finger: the temperature difference at the contact falls, and with it the rate at which the finger loses energy. Same temperature of the cubes, **different rate of transfer**.

A note on the coursebook. The coursebook writes that on touching wood “*your finger loses no more thermal energy*”. As long as the wood is colder than the finger, energy keeps passing: the finger loses *less*, not *none*. What matters is the rate, and the rate is small, not zero.

Let us apply it to the sea. Skin at about 33 °C, water at 20 °C: water conducts about 23 times better than air, so energy leaves the skin much faster into the water than into air at the same temperature. Same temperature, different rate of transfer: answer (b) seems to hold. But something does not add up.

Before moving on. The water in contact with the skin takes in energy and warms up. Why does the skin not end up wrapped in a layer of warm water, which would insulate it a little? What happens to that layer?

Insulators: air is the key

(slide 12)

Air is a very poor conductor: **trapped** air insulates. Glass wool, wool, polystyrene and feathers are mostly air held in small spaces. That is why two thin layers of clothing are warmer than one thick layer: between them there is a layer of air.

Why only *trapped* air? Because free air also carries energy in another way, by moving. That is the next mechanism.

A note on the coursebook. The coursebook writes that double-glazed windows “*usually have a vacuum*” between the panes. Ordinary double glazing contains air or argon in a thin, sealed layer, narrow enough to almost completely prevent convection; that is why conduction and convection are small, not zero. Windows with a true vacuum exist but are rare and expensive.

Convection: where is the element of the kettle?

(slide 13)

An electric kettle heats the water with a heating element.

Before moving on. Is the element at the top, halfway up, or at the bottom? Why exactly there?

It is at the bottom. We will see why shortly; keep it as a test of the explanation.

What is convection?

(slide 14)

Convection is the transfer of thermal energy through a fluid by the movement of the fluid itself.

A **fluid** is a liquid or a gas, because it can flow. Hot fluid moves, carrying energy from a warmer place to a cooler one: its movement is called a **convection current**. There is no convection in solids, because their particles stay in fixed positions. In a fluid there would also be conduction, but it is weak: the transfer is mainly due to the motion of the fluid.

A way to remember the difference: in conduction the material **does not move**; in convection it **moves**.

How to read the animation: convection

(slide 15–16)

The animation shows a tank of water in the particle model (figure 2): each dot is a group of particles and the spacing between dots shows the density.

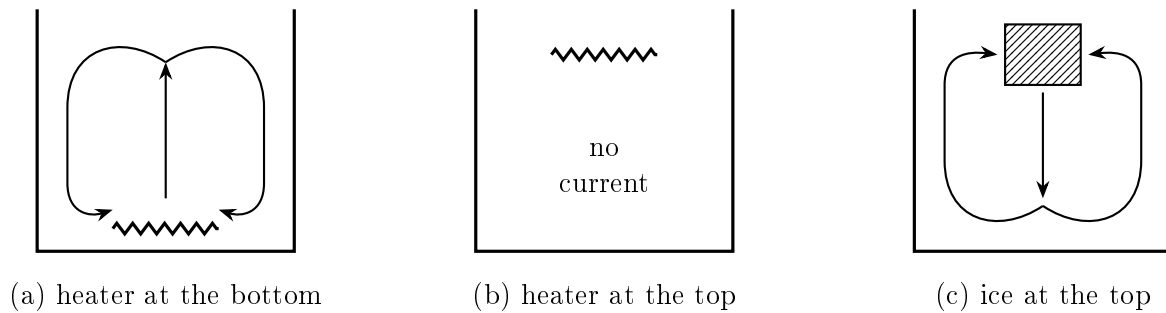


Figure 2: The three set-ups of the animation. The arrows show the convection current: it rises where the fluid is hot and sinks where it is cold (sketch).

What I change. I choose the *source* of the temperature difference: heater or ice cube. Then the *position* of the source, from the bottom to the top of the tank, and the *power* (I start at 80 %). I can switch the flow arrows on or off. Two thermometers measure the temperature in the top 20 % and in the bottom 20 % of the tank; a graph follows them in time.

What I observe. Hot particles (red) are further apart and rise; cold particles (blue) are closer together and sink; the arrows show the circulation. The numbers from the animation at $t = 96$ s, with power at 80 %, are these.

Set-up	Start	T_{top}	T_{bottom}
heater at the bottom	20 °C	36.7 °C	51.2 °C
heater at the top	20 °C	39.2 °C	20.8 °C
ice at the top	25 °C	15.8 °C	16.7 °C
ice at the bottom	25 °C	25.0 °C	11.7 °C

With the heater at the bottom *all* the water warms: in less than a minute the top thermometer has already passed 30 °C (the heated water has risen all the way there), and the bottom, next to the heater, is the hottest point. With the heater at the top only the upper layer warms: the bottom stays at 20.8 °C, almost as at the start. With ice at the top the whole tank cools (top and bottom almost equal); with ice at the bottom only the bottom cools.

What it tells us. Energy travels because the fluid moves, and the engine of the motion is a difference in density: the source goes where it creates the longest current. The heater goes at the bottom, the ice at the top (and for the same reason the freezer compartment of a fridge is at the top).

Why does hot fluid rise?

(slide 17)

Step by step.

1. The fluid is heated: its particles move faster (higher average kinetic energy).
2. It **expands**: the same mass takes up more volume, the particles move further apart. This is the thermal expansion we studied in September.
3. The **density** $\rho = \frac{m}{V}$ decreases, because m stays constant and V increases: the hot fluid is *less dense*.
4. The denser, colder fluid around it pushes it upwards; cold fluid sinks to take its place: a convection current.

A note on the coursebook. The coursebook writes that heated air “*becomes lighter*” and that a less dense material “*is lighter*”. The mass of the fluid has not changed (the fluid does not become “lighter”): the density has changed. The correct phrase is *less dense*. The only apparent exception is the hot-air balloon, where heated air leaves through the opening at the bottom and less mass remains in the same volume; but the criterion is still density.

Convection at work

(slide 18)

- **The kettle.** The element is at the bottom: the water touching it warms, expands and rises; the cold, dense water sinks. If the element were at the top, only the upper layer would warm.
- **A heater in a room.** The air near the heater warms and rises; cooler air arrives to take its place. In this way the energy is shared through the whole room.
- **The fridge.** The freezer compartment is at the top: cold air sinks, cools the food below, and warm air rises to be cooled in turn.
- **A cavity wall.** The air in the cavity carries energy from one wall to the other by convection. Filling it with insulating foam stops the air from moving: the foam conducts a little, but by blocking convection the overall result improves.

Back to the sea: the layer of water is replaced

(slide 19)

Back to the question we left open. The water touching the skin warms up: it becomes less dense, moves away and cold water arrives. The skin never ends up with a “coat” of warm water. In air the same thing happens with the wind: a breeze carries away the thin layer of warm air around the skin.

So in water there is conduction, far more efficient than in air, *plus* convection that continuously replaces the layer in contact with the skin. Yet the Sun also warms someone lying still on the beach. How does that energy get here?

Radiation: from the Sun to us

(slide 20)

Before moving on. The Sun is 150 million kilometres away. Between us and the Sun there is almost nothing. How does thermal energy reach the Earth: by conduction, by convection, or in some other way?

In the vacuum of space there is no material to pass through or to set in motion: conduction and convection are ruled out. Only one mechanism is left, which needs no material at all: **radiation**.

Infrared radiation

(slide 21)

- It is emitted by **all** objects: the hotter the object, the more it emits each second.
- It is an electromagnetic wave: it travels through a **vacuum** and in straight lines.
- It warms the object that **absorbs** it.
- It is invisible to the eye, felt by the skin, seen by a thermal camera.
- A hot object **and** a cold one both emit and absorb: the net transfer goes from hot to cold because the hot one emits more than it absorbs.

A note on the coursebook. The coursebook writes that radiation is “*the only form of thermal energy transfer which does not involve the movement of particles*”. This is not the right distinction: in conduction too the atoms do not travel (they vibrate in place; only the free electrons of metals move). The real difference is another: conduction and convection need a *material*, radiation does not. The coursebook says it right afterwards (“*does not need a medium*”); that is the sentence to remember.

In which part of the spectrum?

(slide 22)

Every object above 0 K emits electromagnetic radiation. But which kind? Thermal radiation is not of a single colour: it is a continuous spectrum, with a maximum at a certain wavelength that depends on the temperature. **Wien’s law** (beyond the syllabus) says that

$$\lambda_{\max} = \frac{b}{T}, \quad b = 2.898 \times 10^{-3} \text{ m K},$$

where $\lambda_{\max}$ is the wavelength at which the emission is greatest and T the absolute temperature. The hotter the object, the more the maximum moves towards short wavelengths.

Object	T (K)	$\lambda_{\max}$	region
human skin	310	9.3 μm	infrared
red-hot iron	1000	2.9 μm	infrared (and a red glow)
lamp filament	3000	0.97 μm	near infrared (and visible)
the Sun	5800	0.50 μm	visible light

For example, for the skin: $\lambda_{\max} = \frac{2.898 \times 10^{-3}}{310} = 9.35 \times 10^{-6} \text{ m} \approx 9.3 \mu\text{m}$.

A note on the coursebook. The syllabus and the coursebook speak of thermal radiation as infrared radiation. At everyday temperatures this is right: the peak of bodies at 20 °C–40 °C falls in the infrared. But it is not a property of “radiation” in general: red-hot iron also emits visible red light, and the Sun peaks in visible light. Thermal radiation is a continuous spectrum whose maximum moves with T .

One question remains, which we will use as a bridge to the next topic. What distinguishes the infrared emitted by the skin from the light emitted by the Sun? A quantity we do not have yet: the **wavelength**. We will introduce it in the lesson on the electromagnetic spectrum.

Colour and finish of the surface

(slide 23)

Matt (dull) black surface	Shiny silver or white surface
good absorber	poor absorber
good emitter	poor emitter
poor reflector	good reflector

A surface that is good at absorbing is good at emitting: the two properties always go in pairs. It is a general fact (Kirchhoff’s law, only qualitative here): the same black surface that heats up so much in the Sun is also the one that cools fastest at night.

A note on the coursebook. The rule “shiny or white = poor emitter” is the simplified rule of the coursebook and of the exam, and it is right for shiny surfaces and for white with respect to sunlight (it reflects it). For the infrared emitted by objects at room temperature the *finish* matters more than the colour: a matt white paint emits infrared almost as well as a black one. Colour decides what happens to visible light; for thermal infrared the nature of the surface decides. For the exam use the coursebook’s rule; for us, it is useful to know why it is a simplification.

Two cans

(slide 24)

The coursebook proposes an experiment (Experimental Skills P3.01): two identical cans with the same water and the same lid, one matt black and one shiny silver, at the same distance from a lamp.

Before moving on. Which one has the thermometer that rises faster? And if both start hot, which one cools faster?

Answer: the black one, both times. Under the lamp the black can absorbs more; when cooling the black can emits more. Let us see it with the animation.

How to read the animation: radiation

(slide 25–26)

This is the richest animation, and it is worth understanding well what is inside it (figure 3).

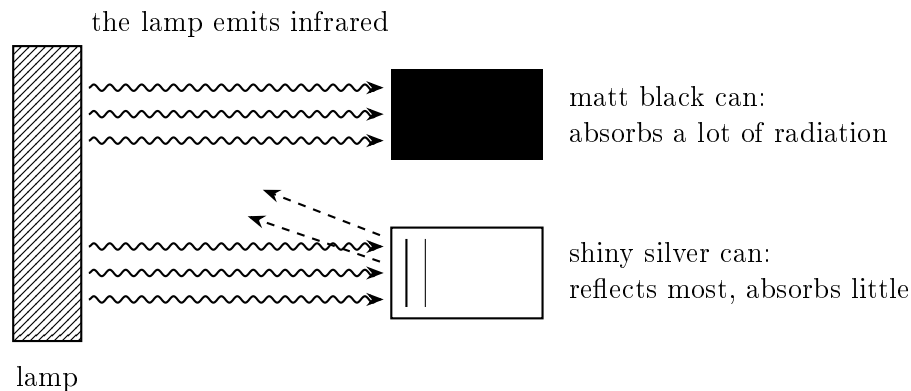


Figure 3: The heating in the animation. Wavy lines are the absorbed radiation; dashed arrows are the radiation reflected by the shiny can (sketch).

What I change. Four controls. The *experiment*: “lamp heats the cans” or “hot cans cool down”. The *lamp temperature* (I start at 600 °C). The *finish of the lower can*, from shiny silver to matt black (the upper one is always matt black). And the *space around the cans*: air or vacuum.

What I observe. The wavy lines between the lamp and the cans are darker and denser when more energy passes; on the shiny can the reflected rays are visible. There are two thermometers, a graph $T(t)$ for each can, and two numbers giving the temperature and the rate of change in °C per second. The time is the model’s time, not real seconds: the numbers are illustrative, and the black can gives the same result in every run.

Air and vacuum: what changes. This is the part to understand well.

- **In air** a can exchanges energy in three ways: radiation, and conduction and convection with the air in contact. In **vacuum** only radiation is left.
- The colour (the finish) acts **only** on radiation, and with the same factor in absorbing and in emitting. The exchange with the air does not depend on colour.
- A can warms until the energy it absorbs each second equals the energy it loses. At that point the temperature stops rising.

In vacuum. The energy absorbed from the lamp and the energy emitted by the can are both multiplied by the factor of the surface. That factor appears on both sides and cancels: the final temperature is the **same** for the black can and for the shiny one. The difference is only the rate: the shiny can gets there much more slowly, because it absorbs (and emits) little. In the model, both tend to about 164 °C; after 120 seconds the black can has reached it, the shiny one is still at about 78 °C (figure 4).

In air. To the loss by radiation is added the loss by conduction and convection, which does not depend on colour. For the black can radiation dominates and it stops at about 118 °C. For the shiny one the absorption is small and a small loss to the air is enough to balance it: it stops at about 41 °C. In air, therefore, colour matters much more.

Cooling. With the experiment “hot cans cool down” both start at 90 °C and the lamp is off. After 30 seconds of the model:

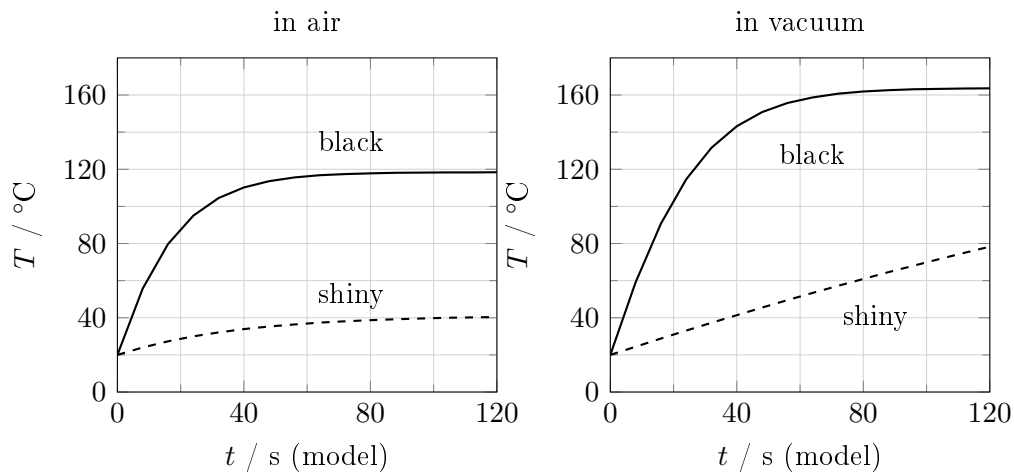


Figure 4: Heating under the lamp at 600 °C from 20 °C, in air and in vacuum. Solid line: black can; dashed: shiny can. Values from the model in the animation.

Can	in air	in vacuum
black	37 °C	54 °C
shiny	52 °C	85 °C

The black can cools faster than the shiny one in both cases. In vacuum the cooling is slower for both, and the shiny one loses almost nothing (from 90 to 85 °C in 30 seconds): this is the principle of the vacuum flask.

What it tells us. That energy crosses empty space, and that the surface decides how much passes. And that to understand a real experiment you must count *all* the channels of loss, not only the one you are interested in.

Air or vacuum, in one picture

(slide 27)

Figure 5 sums up the comparison. In air a hot can loses energy in three ways; in vacuum in only one.

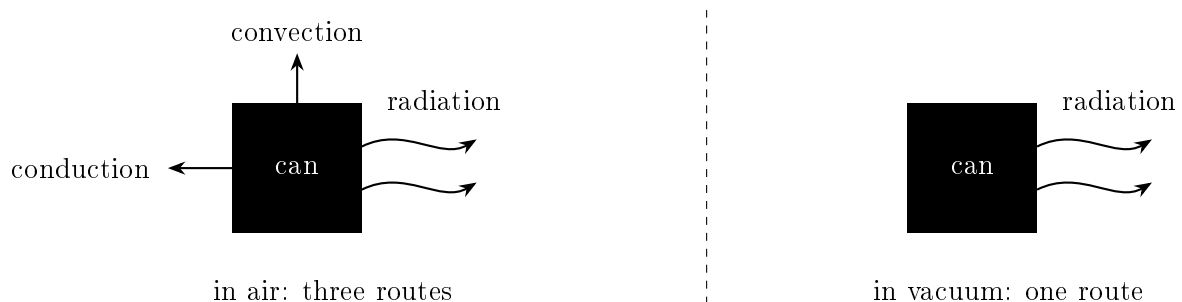


Figure 5: A hot can in air and in vacuum (sketch).

Beakers in a room at 20 °C

(slide 28)

In a room at 20 °C there are three beakers, the first at 80 °C, the second at 20 °C, the third at 5 °C (figure 6). We consider only radiation. Each beaker *emits* each second according to its own temperature and *absorbs* from the room each second according to the temperature of the room, the same for all.

solid line: emitted by the beaker; dashed: absorbed from the room
width of the arrow $\propto$ energy per second

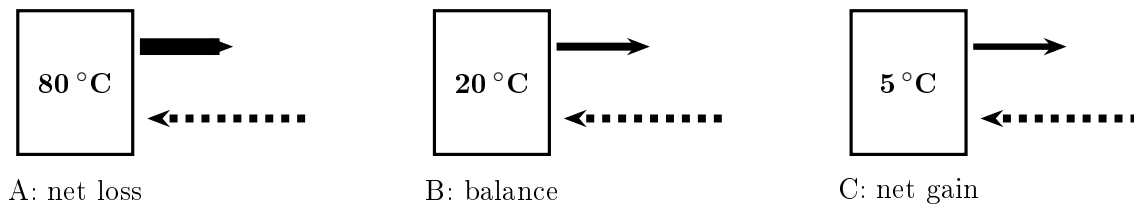


Figure 6: Radiation emitted and absorbed by three beakers in a room at 20 °C (sketch).

Beaker A emits more than it absorbs: it **cools**. Beaker B emits as much as it absorbs: its temperature stays **constant**. Beaker C absorbs slightly more than it emits: it **warms**. The final temperature is the one at which emission and absorption balance: it is the idea behind the temperature of the Earth (Supplement P2.3.3.3).

The widths of the arrows follow the real law: the emitted power grows as the fourth power of the temperature in kelvin (Stefan–Boltzmann law, beyond the syllabus). Compared with the room, the beaker at 80 °C emits $(353/293)^4 \approx 2.1$ times as much; the one at 5 °C emits $(278/293)^4 \approx 0.81$ times as much. In real life conduction and convection also act, and we do not consider them here.

Radiation in everyday life

(slide 29)

- **Car sunshield.** It is shiny: it reflects the radiation of the Sun and the car stays cooler. The black dashboard absorbs it and becomes too hot to touch.
- **White house, light clothes.** They reflect the radiation of the Sun: they absorb little.
- **Campfire.** The warmth on your face is almost all radiation; the air above the fire, instead, warms and rises by convection.
- **Clear night, frost.** The ground radiates towards space and receives little in return, because the clear sky is very cold: it cools even below the temperature of the air. With clouds the ground receives a lot of radiation back, and frost is less likely.

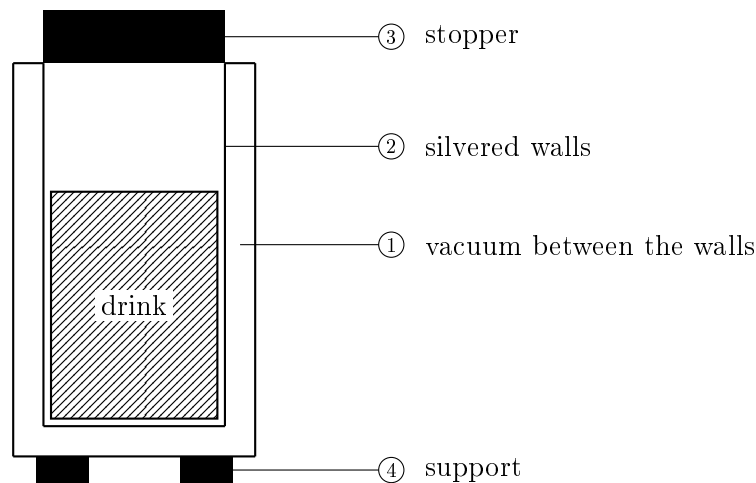


Figure 7: Section of a vacuum flask (sketch, not to scale). There are two walls with a vacuum between them; the faces towards the vacuum are silvered (2).

The vacuum flask

(slide 30)

The vacuum flask uses everything we have seen (figure 7).

1. **Vacuum between the walls:** no conduction and no convection.
2. **Silvered surfaces:** they reflect infrared, so little radiation is emitted and little absorbed.
3. **Plastic stopper:** it stops convection and evaporation at the top.
4. **Glass and supports:** poor conductors.

It also works the other way round, to keep a drink cold: the same barriers slow down the energy coming in.

A solar water heater

(slide 31)

Coursebook question (P3.31): in a solar water heater (figure 8), suggest reasons why (a) the inside of the panel is painted black, (b) the back of the panel is insulated, (c) the cold water enters at the bottom and leaves hot at the top.

(a) A matt black surface is a good absorber of infrared radiation (and of light): it absorbs more energy from the Sun. (b) The insulation reduces the loss by conduction (and convection) from the back. (c) The warmed water expands, becomes less dense and rises: from the highest point starts the convection current that carries the hot water out.

Which mechanism is it?

(slide 32)

Three questions, in this order.

1. Could it happen in space, in a vacuum? If so, it is **radiation** (the only one that needs no material).

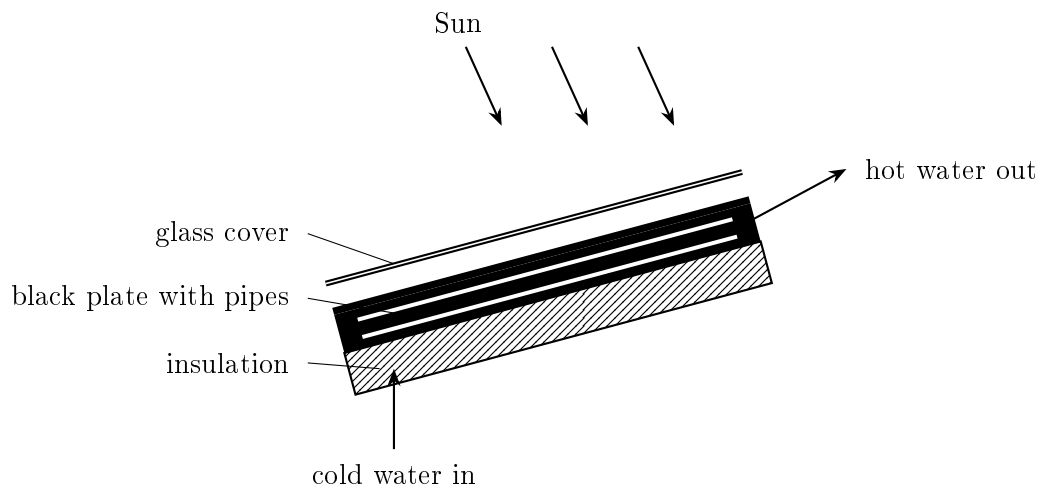


Figure 8: A solar water heater (sketch).

2. Is the material itself moving, and is it a liquid or a gas? Then it is **convection**.
3. Is energy passing through a still material (usually a solid)? Then it is **conduction**.

Often **more than one mechanism acts at once**: in an exercise, name them all.

Back to the sea, one last time

(slide 33)

Why does 20 °C water feel colder than 20 °C air?

- **Conduction**: water conducts about 23 times better than air.
- **Convection**: the water in contact with the skin is replaced all the time (in air the wind does it).
- **Radiation**: in air we also exchange infrared with the surroundings, and it is not a negligible fraction (of the same order as convection in still air); in water it is a drop compared with the other two.

The right answer was (b): same temperature, but water carries energy away from the skin much faster. It is not “only in our head”: it is a real flow of energy, different, and the nerves of the skin feel the *rate* at which we lose energy, not the temperature.

Getting out of the water

(slide 34)

You get out of the shower, or out of the sea. The air is at 20 °C. Wet, you feel even colder than in the water: that is why we dry ourselves.

Before moving on. What is happening, physically? (a) The water on the skin is colder than the air. (b) The water on the skin evaporates. (c) The towel is warm.

Evaporation: a fourth way to lose energy

(slide 35)

It is (b). In the kinetic model (Figure P3.24 of the coursebook) the particles that escape from the surface of a liquid are the **most energetic** ones. Those left behind have a lower average kinetic energy: the liquid cools, and if the liquid is on the skin the skin cools too, which supplies the energy needed.

Evaporation is faster at higher temperature, with a larger surface area, and with **moving air** over the surface (wind, fan). A towel removes the film of water: nothing is left to evaporate. Wet clothes insulate badly: water replaces the trapped air, which is a much poorer conductor, and it also evaporates.

How much energy?

(slide 36)

Let us find an order of magnitude. To evaporate 10 g of water from the skin we need

$$Q = mL = 0.010 \text{ kg} \times 2.4 \times 10^6 \text{ J kg}^{-1} = 2.4 \times 10^4 \text{ J} = 24 \text{ kJ},$$

where L is the specific latent heat of vaporisation of water, about 2.4 MJ kg^{-1} at skin temperature (we will study it with changes of state). At rest the body gives out about 100 W (value from the coursebook). So

$$t = \frac{Q}{P} = \frac{2.4 \times 10^4 \text{ J}}{100 \text{ W}} = 240 \text{ s} = 4 \text{ minutes}.$$

Evaporating just ten grams of water takes from the body all the energy it gives out at rest in four minutes. This is not a detail: it is a fourth way of losing energy, besides conduction, convection and radiation.

Three points to keep

(slide 37)

- **Conduction:** energy passes through a still material, by vibrations and, in metals, by free electrons.
- **Convection:** a fluid carries energy by moving; hot fluid is less dense and rises.
- **Radiation:** infrared waves, no material needed; good absorbers are good emitters.

And also: the skin feels the rate at which it loses energy, not the temperature; and evaporation is a fourth way to lose it.

The notes on the coursebook, in brief

The coursebook says	Better to say
Radiation is the only transfer “without movement of particles”.	In conduction too the atoms do not travel. The difference is that radiation needs no material.
Hot fluid becomes “ <i>lighter</i> ”.	It becomes less dense: the mass has not changed.
Electrons “ <i>get hot</i> ”.	They carry kinetic energy; temperature belongs to a collection of particles.
Vibrations explain only “poor conductors”.	Vibrations occur in every solid; in metals the electrons are added.
With wood the finger “ <i>loses no more thermal energy</i> ”.	It loses less, not none.
“ <i>Heat will quickly reach the petroleum jelly.</i> ”	It is thermal energy that is transferred: heat is not a thing that travels.
Double glazing “ <i>usually a vacuum</i> ”.	Usually air or argon, in a thin sealed layer.
Shiny or white: poor emitter.	True for shiny surfaces and for sunlight; for infrared the finish matters more than the colour.
Thermal radiation is infrared.	Only at everyday temperatures: the peak moves with T (Wien).

Exercises

(slide 38–40)

1. State the two states of matter in which convection can happen, and explain why it cannot happen in the others. [2]
2. A container of water is heated by an electric heater at the bottom (figure 9). Describe how the heater heats all the water. [3]

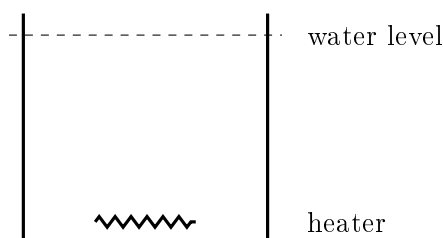


Figure 9: The container of exercise 2.

3. A Leslie cube is a metal container with four different faces: matt black, shiny black, matt white, shiny silver. It is filled with boiling water, so that all the faces are at the same temperature. An infrared detector, always held at the same distance, measures the radiation emitted by each face (figure 10).

- (a) Explain why the detector must stay at the same distance from every face. [1]
 (b) Which face gives the highest reading and which the lowest? Justify your answer. [3]

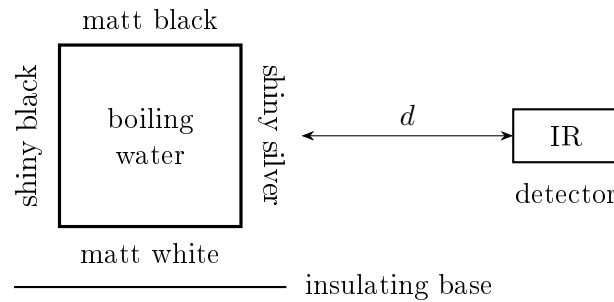


Figure 10: The Leslie cube of exercise 3, seen from above (sketch).

4. A pan of soup is on the hob, with a metal spoon left in it. A person stands 30 cm from the edge (figure 11). For each situation give the main mechanism of thermal energy transfer and justify your answer: (a) the handle of the spoon becomes hot; (b) the soup at the bottom heats the soup at the surface; (c) the person feels their face warming. [6]

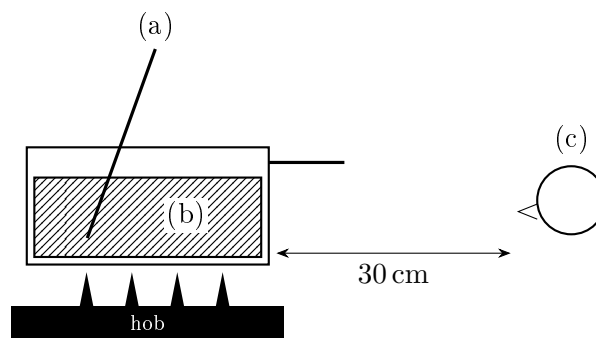


Figure 11: The pan of exercise 4 (sketch).

5. In the experiment with the two cans (one matt black and one shiny silver, both at 90°C at the start, no lamp), the temperature after 30 seconds of the model is:

Can	in air	in vacuum
black	37°C	54°C
shiny	52°C	85°C

- (a) Calculate how far the temperature fell in each of the four cases. [2]
 (b) In which case did the can lose the least energy? [1]
 (c) Explain why the shiny can cools much more in air than in vacuum. [2]
 (d) Give two features of a vacuum flask that make use of these results. [2]
6. An object at absolute temperature T emits radiation with a maximum at wavelength $\lambda_{\text{max}} = b/T$, with $b = 2.898 \times 10^{-3} \text{ m K}$.
 (a) Calculate λ_{max} for human skin, $T = 310 \text{ K}$. [2]
 (b) A star has its maximum at $0.35 \mu\text{m}$. Calculate its temperature and say whether it is hotter or colder than the Sun (5800 K). [3]

- (c) An electric heating element is at 800 K. Calculate λ_{max} and say in which region it falls. [2]
7. An athlete sweats and 50 g of sweat evaporates from the skin. For water $L = 2.4 \times 10^6 \text{ J kg}^{-1}$.
- (a) Calculate the energy needed for the evaporation. [2]
- (b) At rest the body gives out about 100 W. For how long would that energy last? [2]
- (c) Explain why a fan makes us feel cooler without lowering the temperature of the air. [2]

Solutions

1. **Liquids and gases:** they are fluids, their particles can move and flow. In solids the particles stay in fixed positions, so the material cannot move carrying energy.
2. Three ideas, one per mark.
- The water near the heater warms, so its particles move faster and the water **expands**: it becomes **less dense**.
 - The less dense water **rises**.
 - The colder, denser water **sinks** to take its place: the **convection current** carries energy through all the water (figure 12).

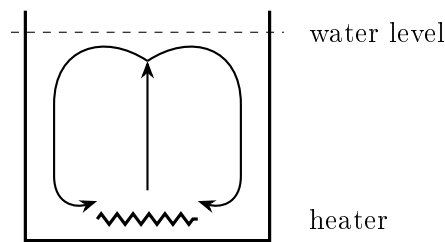


Figure 12: The convection current of exercise 2 (sketch).

3. (a) The reading depends on the distance too: the detector receives less radiation if it is further away. To compare the faces the distance must be the only thing that does not change (a controlled variable): that way the difference between the readings depends only on the surface.
- (b) All the faces are at the same temperature, so the differences depend on the surface. The **highest** reading is from the **matt black** face: it is a good emitter of infrared. The **lowest** is from the **shiny silver** face: it is a poor emitter (good reflector). The shiny black and matt white faces lie in between.
4. (a) *Conduction*: energy passes along the metal spoon, which is a good conductor (vibrations of the atoms and free electrons); the material does not move. (b) *Convection*: the soup at the bottom warms, expands, becomes less dense and rises; the colder, denser soup sinks: a fluid is moving. (c) *Radiation*: the person is beside the pan. Hot air rises, it does not go sideways (this rules out convection), and air conducts very poorly (this rules out conduction): what is left is the infrared emitted by the hot pan, which travels in a straight line and is absorbed by the skin.
5. (a) Fall in temperature, $\Delta T = 90 - T_{30}$:

Can	in air	in vacuum
black	$90 - 37 = 53 \text{ K}$	$90 - 54 = 36 \text{ K}$
shiny	$90 - 52 = 38 \text{ K}$	$90 - 85 = 5 \text{ K}$

(b) The shiny can in vacuum: it fell by only 5 K.

(c) In air the can also loses energy by conduction and convection to the air, and these two mechanisms do not depend on the surface. In vacuum only radiation is left, and a shiny surface is a poor emitter.

(d) The vacuum between the walls (no conduction or convection) and the silvered surfaces (little radiation). The stopper, which stops convection and evaporation at the top, is also acceptable.

6. (a) $\lambda_{\max} = \frac{b}{T} = \frac{2.898 \times 10^{-3}}{310} = 9.348 \times 10^{-6} \text{ m} \approx 9.3 \mu\text{m}.$

(b) $T = \frac{b}{\lambda_{\max}} = \frac{2.898 \times 10^{-3}}{0.35 \times 10^{-6}} = 8.28 \times 10^3 \text{ K} \approx 8\,300 \text{ K}$ (with $0.35 \mu\text{m} = 3.5 \times 10^{-7} \text{ m}$). It is **hotter** than the Sun (5 800 K): maximum at a shorter wavelength, higher temperature.

(c) $\lambda_{\max} = \frac{2.898 \times 10^{-3}}{800} = 3.62 \times 10^{-6} \text{ m} \approx 3.6 \mu\text{m}$: infrared.

7. (a) $m = 0.050 \text{ kg}$; $Q = mL = 0.050 \times 2.4 \times 10^6 = 1.2 \times 10^5 \text{ J} = 120 \text{ kJ}.$

(b) $t = \frac{Q}{P} = \frac{1.2 \times 10^5}{100} = 1\,200 \text{ s} = 20 \text{ minutes}.$

(c) Moving air carries away the vapour and the humid air near the skin: evaporation becomes faster, and with it the loss of energy from the skin. It also replaces the layer of air in contact with the skin (forced convection). The temperature of the air does not change: what changes is the rate at which we lose energy, which is what we feel.