Unit 12

Rate of Heat Flow

This unit online, with its interactives:
science-playground.com/s/11f12

On a winter morning in Bhaktapur, the steel chair on the veranda feels icy and the wooden bench beside it doesn't, though both have sat in the same cold air all night and are at the same temperature. Pour boiling water into a steel tumbler and you can't hold it; pour it into a clay cup and you can. Something about each material decides how **fast** heat moves through it.

The last unit measured heat: how much it takes to warm or melt something. This one asks **how fast** heat flows, and by which road. You will meet the three roads, conduction, convection and radiation; put a number on how well a material conducts, and measure it with Searle's apparatus; see why a quilt keeps you warm and why a thermos flask has a vacuum and silvered walls; and finish with the fourth-power law of radiation, which let a physicist in Vienna work out the temperature of the Sun without leaving his room.

12.1 Introduction

A STORY FROM SCIENCE

Josef Stefan, the man who weighed the Sun's heat

Josef Stefan (1835–1893) was born to Slovene parents in St. Peter, a village near Klagenfurt in southern Austria. He studied at the University of Vienna, graduating in 1857, and stayed there all his life: lecturer in mathematical physics in 1858, full professor of physics in 1863, and director of its Physical Institute from 1866. One of his students was Ludwig Boltzmann.
In 1879 Stefan noticed something in another scientist's measurements of a glowing platinum wire: when its absolute temperature rose from 798 K to 1473 K, it radiated about 11.7 times as much heat. And $(1473/798)^4 \approx 11.6$. The heat radiated, he proposed, goes as the **fourth power** of the absolute temperature. He at once used the rule to estimate the temperature of the Sun's surface, and got about 5430 °C, close to the modern value. Five years later Boltzmann derived the same law from the theory of heat and light, and it became the **Stefan–Boltzmann law** (Section 12.10). It was one of the first steps towards understanding black-body radiation, the puzzle that led, in 1900, to the quantum idea.

Heat flows from a hotter body to a colder one as long as there is a difference of temperature between them, and nothing can stop it completely: the best insulator only slows it down. The hotter body loses energy and cools, the colder one gains it and warms, until both are at the same temperature (Unit 9).



Figure 12.1 *Josef Stefan (1835–1893).*
Photo: K. Schönbauer, Public domain

Heat travels by three roads:

- **Conduction.** Put one end of a steel spoon in hot tea and soon the other end is warm. The metal itself doesn't move; heat passes from particle to particle through it.
- **Convection.** Heat a pot of water from the bottom and the top soon warms too. The warm water itself rises, carrying its heat with it, and cooler water sinks to take its place.
- **Radiation.** Sit near a fire, or in the sun, and you feel warm, though the air between may be cold. Heat crosses the space as electromagnetic waves, needing no material at all; that is how the Sun's heat reaches us across the vacuum of space.

In short: **conduction** passes heat by the vibrations and collisions of particles in a solid (or a still fluid), with no particle traveling; **convection** carries heat by the bulk movement of a fluid itself; **radiation** sends heat as electromagnetic waves, with no medium at all.

12.2 Conduction

Heat one end of a metal rod. The atoms there vibrate about their places more and more strongly: they have more kinetic energy than their neighbors in the colder part. Each atom is held to its neighbors by forces like springs, so its harder vibrations jostle the next atoms, which jostle the next, and energy passes along the rod from the hot end towards the cold one. No atom leaves its place; only the energy of vibration travels. This is **conduction**.

In **metals** there is a second, faster carrier. A metal has **free electrons** that move about among its atoms. In the hot region they move faster, and as they wander into the colder region they share that energy with it. This is why metals, which have many free

electrons, conduct heat far better than wood, glass or plastic, which have none, and why good conductors of electricity (copper, silver, aluminium) are also good conductors of heat.

Conduction is the transfer of heat from a hotter part of a body to a colder part, or between bodies in contact, by the vibrations and collisions of its particles (and, in metals, by free electrons), without the particles themselves moving from place to place.

- Conduction needs a **material medium**: there is none in a vacuum.
- It happens mainly in **solids**. Liquids and gases conduct too, but poorly, and in them convection usually carries far more heat.
- A material's ability to conduct heat is measured by its **thermal conductivity** (Section 12.4). Metals are **good conductors**; materials that conduct heat poorly, such as wood, paper, plastic, cotton, wool and air, are **bad conductors** or **insulators**.

Check 1

Why do metals conduct heat much better than wood?

a their atoms are heavier
b their atoms move from the hot end to the cold end
c they have free electrons that carry energy quickly through them
d they are denser, so they have more atoms to vibrate

Conduction in daily life

Most of the examples below use one fact: **still air is a very poor conductor**, about five times poorer than wood and 15 000 times poorer than copper. Trap air in small pockets, so that it can't move and carry heat by convection, and you have an insulator.

1. **Two thin jackets are warmer than one thick jacket** of the same total thickness: the layer of air trapped between them adds to the insulation.
2. **Double walls in cold places.** The ice houses of the Arctic, and many houses in cold countries, have two walls with air between them: the trapped air slows the loss of heat from inside to outside.
3. **Double-glazed windows** in cold countries have two panes of glass with a thin layer of air (or gas) between them.
4. **Cold-storage rooms** have thick walls of insulating material, so that heat from outside leaks in slowly.
5. **A tight glass stopper** can be loosened by dipping the bottle's neck in warm water. Glass is a poor conductor, so the neck warms and expands before the heat reaches the stopper, and the stopper comes free.
6. **Pans, kettles and pressure cookers** are made of metal, so that heat passes quickly to the food, but their handles are wood, Bakelite or plastic, so that the heat doesn't reach your hand.
7. **Woolen clothes** are full of tiny pockets of air. Wool and air are both poor conductors, so heat from the body escapes slowly, and wool keeps you warm in winter.
8. **A thermos flask** has a vacuum between its double walls: with no medium, there is no conduction (or convection) across the gap (Figure 12.2; Exercise 18).
9. **An iron chair feels colder than a wooden one** in winter, though both are at the same temperature: iron conducts heat away from your skin quickly, wood hardly at all.
10. **Ice packed in sawdust** inside a double-walled ice box, wrapped in sacking, melts slowly: sawdust, the air in it, and the sacking are all poor conductors.
11. **A quilt** (सिरक) is filled with fluffy cotton, which traps air in its spaces. A newly made quilt, its cotton freshly carded, holds much more air than an old, pressed-down one, and is warmer. That is why the cotton of an old quilt is taken out and fluffed up again by a cotton carder before winter.

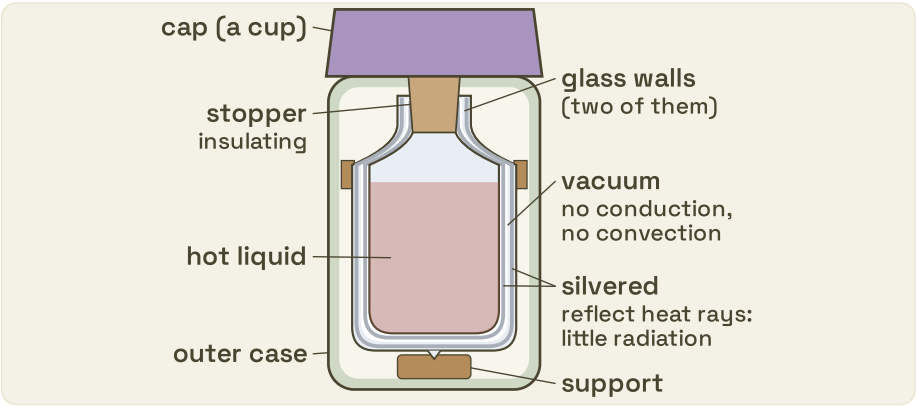


Figure 12.2 *A thermos flask in section: a double-walled glass bottle with a vacuum between the walls, silvered on the surfaces facing the vacuum, closed by an insulating stopper and held on a soft support inside a protective case.*

DID YOU KNOW?

Snow keeps things warm

Fresh snow is about nine-tenths air. Its thermal conductivity is only about a thirtieth of solid ice's, not much more than still air's. That is why snow on a field protects the wheat below from hard frost, why animals in the Himalaya dig into snowbanks to sleep, and why an igloo, built of blocks of packed snow, can be 20 to 30 degrees warmer inside than the Arctic air outside, warmed only by the people in it and a small lamp.

Sample questions

12.3 Temperature gradient

Hold one end of a metal rod in a flame. Close to the flame the rod is very hot; a little farther along it is warm; at the far end it may still be cool. The temperature changes along the rod, and how quickly it changes, degree by degree, with distance, is what drives the heat along.

The **temperature gradient** at a point is the rate at which the temperature changes with distance along a given direction:

$$\text{temperature gradient} = \frac{d\theta}{dx}$$

where $d\theta$ is the small change of temperature over a small distance dx. Its SI unit is the kelvin per meter, K/m (the same as °C/m, since a change of 1 K is a change of 1 °C). Like a slope, it has a direction: the direction in which the temperature changes fastest. Heat flows **down** the gradient, from hot to cold, the way water runs down a slope.

Temperature along a conducting rod

Put one end of a rod of length l in a **hot reservoir** kept at θ_1 (a box of steam, say) and the other in a **cold reservoir** kept at θ_2 (melting ice). At first the rod warms up all along its length. After a while each point settles to a steady temperature that no longer changes: the rod has reached its **steady state**. Every point then passes on exactly as much heat as it receives; none is stored.

- **A lagged rod.** Wrap the rod's curved surface in a thick layer of insulation (**lagging**: felt, cotton wool, foam), so that no heat leaks from its sides. In the steady state, all the heat that enters at the hot end flows through every cross-section and out at the cold end. Then the temperature falls **uniformly** along the rod: a graph of temperature against distance is a **straight line**, and the temperature gradient is the same everywhere:

$$\frac{\Delta\theta}{\Delta x} = \frac{\theta_1 - \theta_2}{l} = \text{constant}$$

- **An unlagged rod.** Leave its sides bare, and the rod loses heat to the air all along its length, most where it is hottest. Each section passes on less heat than it receives, so the temperature falls **steeply near the hot end and more gently farther on**: the graph is a curve, and the gradient is not uniform. For a long rod in air, the curve is close to an exponential fall.

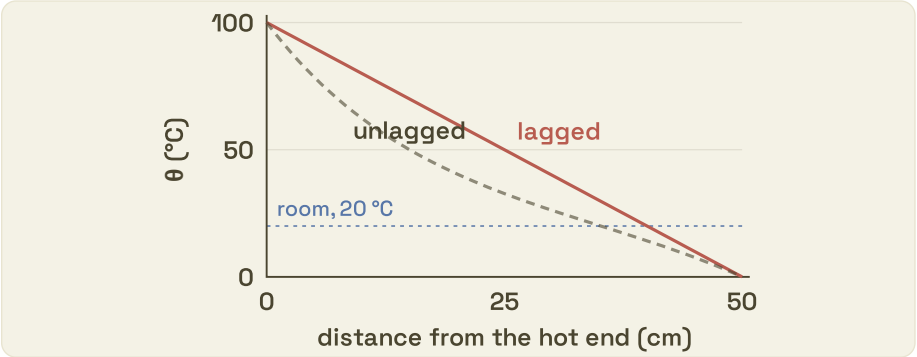


Figure 12.3 *Temperature along a rod 50 cm long from a steam box at 100 °C to melting ice at 0 °C, in the steady state. Lagged (red), it falls uniformly, in a straight line. Unlagged (gray, dashed), it loses heat from its sides, falls steeply near the hot end and gently farther on, dipping below the room's 20 °C before it reaches the ice.*

Check 2

In the steady state, the hot end of a well-lagged rod 40 cm long is at 90 °C and the cold end at 10 °C. What is the temperature at the middle?

a 45 °C
b 50 °C
c 60 °C
d 80 °C

12.4 Thermal conductivity

How much heat flows through a wall or a pan bottom each second? Take a slab of material with parallel faces, each of area A, a thickness x apart. One face is kept at a higher temperature θ_1, the other at a lower temperature θ_2, and no heat is lost from its sides (Figure 12.4). In the steady state, experiments show that the rate of flow of heat, Q/t, through the slab is:

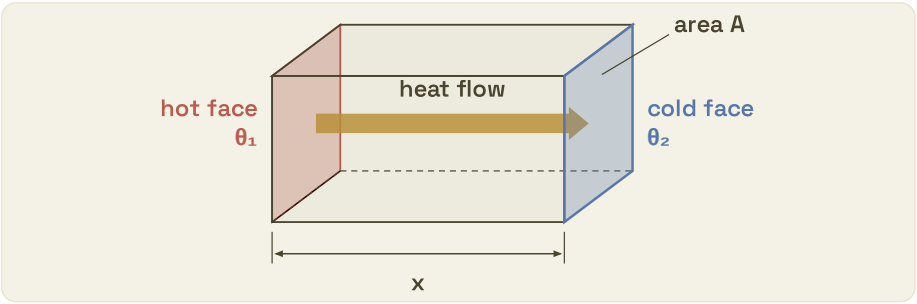


Figure 12.4 *A slab of thickness x, each face of area A. The left face is kept hot at θ_1, the right cold at θ_2; heat flows straight through from the hot face to the cold one.*

1. directly proportional to the **temperature gradient** across it, $\frac{\theta_1 - \theta_2}{x}$ (twice the difference, or half the thickness, twice the flow):

$$\frac{Q}{t} \propto \frac{\theta_1 - \theta_2}{x} \tag{12.1}$$

2. directly proportional to the **area** of each face (two equal slabs side by side carry twice as much):

$$\frac{Q}{t} \propto A \tag{12.2}$$

Combining (12.1) and (12.2), $\frac{Q}{t} \propto A\,\frac{\theta_1 - \theta_2}{x}$, and with a constant of proportionality k:

$$\frac{Q}{t} = kA\,\frac{\theta_1 - \theta_2}{x} \tag{12.3}$$

The constant k depends only on the material of the slab. It is the material's **thermal conductivity** (also called its coefficient of thermal conductivity). Rearranging,

$$k = \frac{Q/t}{A\left(\dfrac{\theta_1 - \theta_2}{x}\right)}$$

so if $A = 1\ \text{m}^2$ and the temperature gradient $\dfrac{\theta_1 - \theta_2}{x} = 1\ \text{K/m}$, then $k = Q/t$. Hence:

The thermal conductivity of a material is the rate of flow of heat per unit area of cross-section through it, in the steady state, when the temperature gradient across it is one unit. Equivalently, it is the heat flowing per second, in the steady state, between opposite faces of a unit cube of the material kept at a unit difference of temperature.

Unit. From $k = \dfrac{(Q/t)\,x}{A(\theta_1 - \theta_2)}$:

$$\text{unit of } k = \frac{\text{J/s} \times \text{m}}{\text{m}^2 \times \text{K}} = \frac{\text{W}}{\text{m K}} = \text{W/(m K)}$$

(W m^{-1} K^{-1} in negative powers).

Dimensions. $[k] = \dfrac{[\text{ML}^2\text{T}^{-3}][\text{L}]}{[\text{L}^2][\text{K}]} = [\text{MLT}^{-3}\text{K}^{-1}]$.

CAREFUL

The temperature difference, not the temperature

The heat flow depends on the **difference** $\theta_1 - \theta_2$, which is the same in kelvin and in °C. You never need to convert to kelvin in the conduction formula; you **do** in the radiation laws later in this unit.

The thermal conductivities of some common materials, near room temperature:

Material	k (W/(m K))	Material	k (W/(m K))
Silver	429	Ice	2.2
Copper	401	Glass	about 1
Aluminium	237	Brick	about 0.6
Brass	109	Water	0.6
Iron	80	Wood	0.1–0.2
Steel	about 50	Cork, wool	about 0.04
Stainless steel	about 16	Still air	0.026

Silver and copper conduct about **15 000 times** as well as still air. The good conductors are all metals; the poor ones are non-metals, and the best insulators (cork, wool, cotton, foam, snow) are mostly trapped air.

WORKED EXAMPLE

Heat through a window

A glass window pane is 1.0 m by 1.5 m and 4.0 mm thick. The inner face is at 18 °C and the outer face at 10 °C. Find the rate at which heat flows through it. (k for glass = 1.0 W/(m K).)

Answer

$A = 1.0 \times 1.5 = 1.5\ \text{m}^2$, $x = 4.0 \times 10^{-3}\ \text{m}$, $\theta_1 - \theta_2 = 18 - 10 = 8\ °\text{C} = 8\ \text{K}$.

$$\frac{Q}{t} = kA\,\frac{\theta_1 - \theta_2}{x} = 1.0 \times 1.5 \times \frac{8}{4.0 \times 10^{-3}} = 3000\ \text{W}$$

3 kW, as much as three electric heaters, through one thin pane. (In practice it is far less: a thin layer of still air clings to each side of the glass and adds much more insulation than the glass itself, so the glass's own faces are much nearer each other in temperature than the room and the street.)

Check 3

A slab conducts heat at 40 W. If its thickness is doubled and its area is doubled, with the same temperatures on its faces, the rate of flow becomes:

a 10 W
b 40 W
c 80 W
d 160 W

Sample questions

12.5 Thermal conductivity of a good conductor: Searle's method

Measuring k for a metal is not easy: heat flows through a metal so readily that it escapes from its sides almost as easily as along it, and a short, thick piece shows only a tiny temperature difference. The English physicist George F. C. Searle (1864–1954), of the Cavendish Laboratory in Cambridge, designed an apparatus that solves both problems: a **long, thick bar**, well lagged, heated at one end and cooled at the other by flowing water, whose heat can be measured.

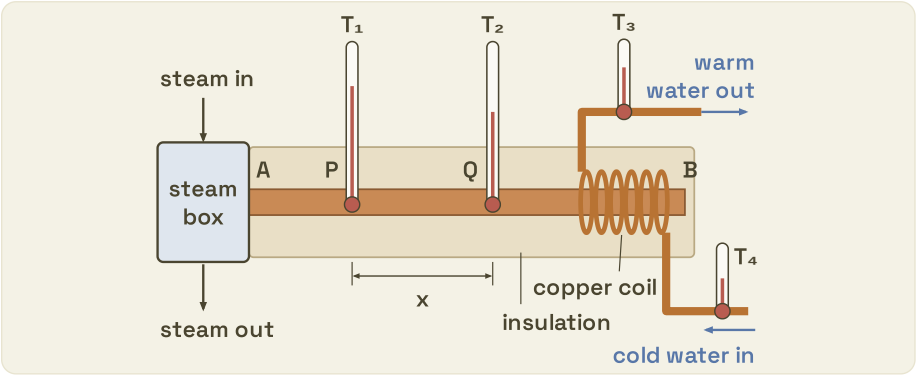


Figure 12.5 *Searle's apparatus. Steam passes through the box at end A of the metal bar AB. Thermometers T_1 and T_2 sit in mercury-filled holes P and Q, a distance x apart. Water flows steadily through a copper coil wound round end B, in at T_4 and out at T_3; the warm water is collected and weighed. The whole bar is packed in insulation.*

The apparatus (Figure 12.5).

- A metal bar AB of uniform cross-section A (a thick copper rod), packed inside a box of insulating material (felt or cotton wool) so that no heat escapes from its sides.
- At end A, a **steam box**: steam passes through it continuously, keeping that end at about 100 °C.
- Near end B, a **copper coil** wound tightly round the bar. Cold water flows steadily through it from a constant-pressure supply, takes up the heat arriving at B, and flows out warmed. Thermometer $\mathbf{T_4}$ reads the temperature θ_4 of the water flowing in and $\mathbf{T_3}$ the temperature θ_3 of the warm water flowing out; the warm water is collected in a beaker and weighed.
- Two holes **P** and **Q** drilled into the bar, a distance x apart, each filled with a little mercury for good thermal contact, hold thermometers $\mathbf{T_1}$ and $\mathbf{T_2}$, which read θ_1 and θ_2.

Method. Start the steam and the water. At first all four thermometers change as the bar warms. Wait, often an hour or more, until all four readings are **steady**: the bar has reached its steady state, so every cross-section passes on the same heat each second, and all of it reaches the water. Then record $\theta_1, \theta_2, \theta_3, \theta_4$, collect the water flowing out for a measured time t, and weigh it: mass m. Measure x, and the bar's diameter to find A.

Theory. In the steady state:

1. Heat flows through the bar between P and Q at the rate
$$\frac{Q}{t} = kA\frac{\theta_1 - \theta_2}{x} \qquad (\theta_1 > \theta_2)$$
2. The water, of specific heat capacity s, takes up heat at the rate
$$\frac{Q}{t} = \frac{ms(\theta_3 - \theta_4)}{t} \qquad (\theta_3 > \theta_4)$$
3. No heat is lost from the lagged bar and none is stored, so the two rates are equal:
$$kA\frac{\theta_1 - \theta_2}{x} = \frac{ms(\theta_3 - \theta_4)}{t}$$
4. Solving for k:
$$\boxed{k = \frac{ms(\theta_3 - \theta_4)\,x}{At(\theta_1 - \theta_2)}} \tag{12.4}$$

Every quantity on the right is measured, so k is found.

Why this design works:

- The bar is **thick**, so plenty of heat flows through it and the water's rise in temperature is large enough to measure well.
- It is **long**, with P and Q far apart, so $\theta_1 - \theta_2$ is several degrees, not a fraction of one.
- It is **lagged**, so the heat that passes P also passes Q and reaches the water: the gradient is uniform (Section 12.3).
- The **mercury** in the holes makes good contact between bar and thermometer bulb.

For a **poor conductor** (glass, cardboard, ebonite) this method fails: so little heat gets through a long bar that the water hardly warms. A poor conductor is measured as a thin, wide disc instead (Lee's disc method), so that A is large and x small.

CAREFUL

Wait for the steady state

Readings taken while the thermometers are still rising are useless: part of the heat entering the bar is then still warming it up, not passing through, and (12.4), which assumes every cross-section carries the same heat, doesn't hold.

WORKED EXAMPLE

Ice in a wooden box

Estimate the rate at which ice melts in a wooden box 2.5 cm thick, of inside measurements 100 cm × 60 cm × 40 cm, if the temperature outside is 35 °C. (Thermal conductivity of wood 0.168 W/(m K), specific latent heat of fusion of ice 336 000 J/kg.)

Answer

The ice keeps the inside of the walls at 0 °C. The heat flowing in through the walls each second melts the ice.

Area of the six walls (inside measurements): $A = 2(lb + bh + lh) = 2(100 \times 60 + 60 \times 40 + 40 \times 100) = 24\,800$ cm² = 2.48 m².

$x = 2.5 \times 10^{-2}$ m, $\theta_1 - \theta_2 = 35 - 0 = 35$ °C.

Heat flowing in per second = heat taken per second by the melting ice:

$$kA\,\frac{\theta_1 - \theta_2}{x} = L\,\frac{dm}{dt}$$

$$\frac{dm}{dt} = \frac{kA(\theta_1 - \theta_2)}{xL} = \frac{0.168 \times 2.48 \times 35}{2.5 \times 10^{-2} \times 336\,000} = \mathbf{1.74 \times 10^{-3}\ kg/s}$$

That is about 1.7 g every second, some 6 kg an hour. (Using the inside measurements underestimates the walls' area a little; a real ice box would also be lined with a better insulator than wood.)

Two layers: a composite wall

Real walls are often made of layers: wood lined with cork, brick plastered on both sides, two panes with air between. In the steady state **the same heat flows through each layer every second**: heat can't pile up at the boundary between them. That one fact solves every layered-wall problem.

WORKED EXAMPLE

Wood lined with cork

An ice box is made of wood 1.75 cm thick, lined inside with cork 2 cm thick. The inner surface of the cork is steady at 0 °C and the outer surface of the wood at 12 °C. Wood conducts heat five times as well as cork. Find the temperature of the boundary between the wood and the cork.

Answer

Let the boundary be at θ, and the conductivity of cork be k, so that of wood is $5k$. Heat flows in from the wood (12 °C outside) through the cork (0 °C inside). For a steady flow, the rates through the two layers are equal (each of area A):

$$5k \times A \times \frac{12 - \theta}{1.75 \times 10^{-2}} = k \times A \times \frac{\theta - 0}{2 \times 10^{-2}}$$

Cancel kA and multiply both sides by 10^{-2}:

$$\frac{5(12 - \theta)}{1.75} = \frac{\theta}{2} \;\Rightarrow\; 10(12 - \theta) = 1.75\,\theta \;\Rightarrow\; 120 = 11.75\,\theta$$

$$\theta = \frac{120}{11.75} = \mathbf{10.2\ °C}$$

Of the 12 °C drop across the wall, 10.2 °C is across the cork and only 1.8 °C across the wood: the poorer conductor takes most of the drop, and does most of the insulating.

YOUR TURN

The woolen glove

A woolen glove insulates a hand as well as a layer of still air 3 mm thick would. Find the rate of heat loss from a hand of surface area 200 cm² on a winter day, when the air is at −3 °C and the skin at 35 °C. (Thermal conductivity of air 0.024 W/(m K).)

Answer

$A = 200\ \text{cm}^2 = 2.00 \times 10^{-2}\ \text{m}^2$, $x = 3 \times 10^{-3}\ \text{m}$, $\theta_1 - \theta_2 = 35 - (-3) = 38\ °\text{C}$.

$$\frac{Q}{t} = kA\,\frac{\theta_1 - \theta_2}{x} = 0.024 \times 2.00 \times 10^{-2} \times \frac{38}{3 \times 10^{-3}} = \mathbf{6.08\ W}$$

12.6 Convection

Liquids and gases are poor conductors, yet a pot of water on a stove is soon hot all through. The water at the bottom, warmed by the flame, **expands**, so it becomes less dense than the cooler water above it. The cooler, denser water sinks and pushes the warm water up, just as a cork is pushed up through water. At the top the warm water spreads out and cools; cooler water sinks at the sides, is warmed at the bottom, and rises in its turn. This steady circulation is a **convection current**, and it carries heat through the whole pot far faster than conduction could.

Convection is the transfer of heat in a fluid (a liquid or a gas) by the actual movement of the heated fluid itself, from a hotter region to a colder one, the colder fluid moving the other way to take its place.

- Convection happens only in **fluids**, liquids and gases, whose particles are free to move. It can't happen in a solid, and it can't happen in a vacuum, which has no particles to move.
- Water and air are heated from **below** by convection: that is why the burner is under the pot, and a room heater on the floor.

Natural and forced convection

Natural (free) convection is driven by gravity alone. Heated fluid expands, becomes less dense, and the buoyant force (upthrust) of the denser fluid round it pushes it up. Without gravity there is no upthrust, and so no natural convection: in an orbiting space station a candle flame is a dim blue ball, not a tall flame, because its hot gases don't rise and fresh air doesn't flow in. The circulation of the atmosphere that makes our daily weather, land and sea breezes, the trade winds and the monsoon are all natural convection.

Forced (artificial) convection is driven by a pump, a fan or a blower, which pushes the fluid round whatever its temperature. Examples:

- the heart pumping blood round the body, carrying heat from the busy organs inside to the skin, where it is lost, and keeping the whole body near 37 °C;
- the fan inside a computer, a laptop or a projector, which blows air past the hot chips to cool them;
- the pump in a car's cooling system, and the fan behind its radiator;

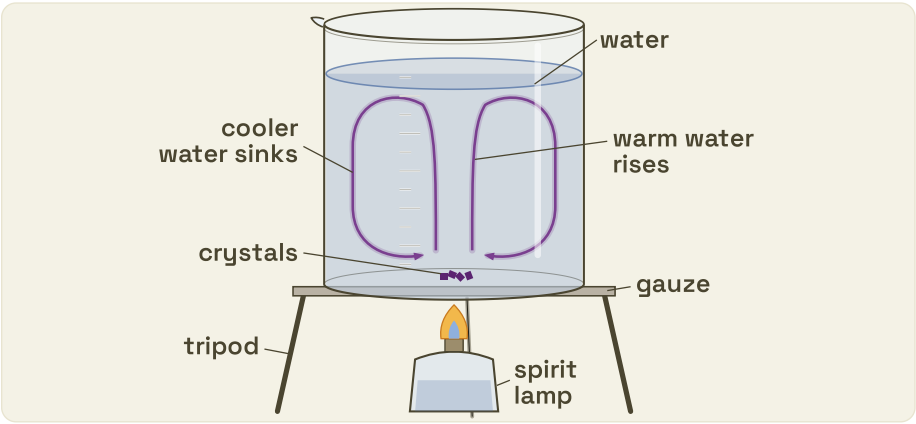


Figure 12.6 *Convection made visible. A few crystals of potassium permanganate at the bottom of a beaker of water, heated from below: the colored water rises in a column over the flame, spreads at the top and sinks down the sides, a convection current.*

- a hair dryer, a fan heater, and the blower of a room air conditioner.

Factors affecting convection

The rate at which a surface gives heat to (or takes heat from) the fluid around it is found by experiment to be

1. directly proportional to the **temperature difference** $\Delta\theta$ between the surface and the fluid: $\frac{Q}{t} \propto \Delta\theta$;
2. directly proportional to the **area** A of the surface exposed to the fluid: $\frac{Q}{t} \propto A$.

Combining them, with a constant of proportionality h:

$$\frac{Q}{t} = hA\,\Delta\theta \tag{12.5}$$

h is the **convection coefficient** (heat transfer coefficient), in W/(m² K). It depends on the fluid and on how fast it moves past the surface: still air gives only about 5–25 W/(m² K), a wind or a fan several times more, and flowing water hundreds to thousands. That is why a fan cools you, why a breeze makes a cold day feel colder (the wind-chill), and why your hand feels colder in cold water than in air at the same temperature. Equation (12.5) is also Newton's law of cooling (Unit 11), written for heat lost by convection.

Check 4

In a space station orbiting the Earth, which way of passing heat no longer works?

a conduction
b natural convection
c forced convection
d radiation

Convection in nature and at home

a. The trade winds. The Sun heats the Earth most strongly near the equator. Air there is warmed, rises, and flows away towards the poles high up; cooler air flows in along the ground to take its place. These steady winds, blowing towards the equator over the oceans, were used by sailing ships for centuries, which is how they got their name. They don't blow due south or due north: the Earth spins from west to east beneath the moving air, so the winds are turned to come **from the north-east** in the northern hemisphere and **from the south-east** in the southern.

b. Sea breezes and land breezes. Water has a much higher specific heat capacity than soil and rock, and the sea mixes its heat through a deep layer. So in the daytime, under the same sunshine, the land warms up much more than the sea. The air over the land is warmed, expands and rises; cooler air from over the sea flows in to take its place: a **sea breeze**, blowing from the sea to the land. At night the land cools faster than the sea, the air over the sea is the warmer and rises, and air flows from the land out to sea: a **land breeze**.

c. Ocean currents. Warm surface currents, such as the **Gulf Stream**, carry warm water from the tropics towards the poles, and cold water returns towards the equator, some of it deep below the surface. The surface currents are driven mostly by the winds; the deep return flow is driven by density, natural convection: near the poles the water is cooled (and made saltier as sea ice forms), becomes denser, and sinks. The Gulf Stream is why north-western Europe is mild for its latitude.

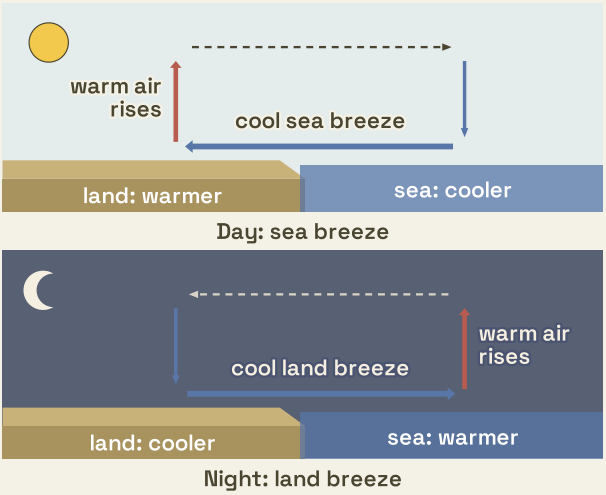


Figure 12.7 *By day the land is warmer than the sea: air rises over the land and the sea breeze blows in from the sea. At night the sea is the warmer: air rises over the sea and the land breeze blows out from the land.*

d. Ventilation. Rooms have **ventilators** near the ceiling. Warm, damp, used air from our breathing rises and leaves through them, and cooler fresh air comes in through the windows and doors below.

e. Chimneys. Hot gases from a fire rise up the chimney, and fresh air, with the oxygen the fire needs, is drawn in at the bottom. The taller the chimney, the stronger the draught. Smoke-free cooking stoves (सुधारिएको चुलो) use a chimney to carry the smoke out of the kitchen.

f. Monsoons. In summer the land of South Asia becomes much hotter than the Indian Ocean. Air rises over the land, and moist air from the ocean flows in to replace it, rising over the hills and the Himalaya and dropping its rain: the summer monsoon, which brings Nepal about four-fifths of its yearly rain. In winter the flow reverses.

DID YOU KNOW?

Why mountain tops are cold

The air is heated mainly from the ground below, by convection, not by the sunlight passing through it. Warm air rising from the ground expands as the pressure falls, and expanding air cools. On average the air is about 6.5 °C colder for every 1000 m of height, which is why it is near freezing at 5000 m on a sunny summer day in the Himalaya, and why the high peaks keep their snow all year.

Sample questions

12.7 Radiation

Stand in the winter sun and you feel its warmth on your face at once, though the air round you may be cold. The heat has crossed 150 million kilometers of almost empty space to reach you. It can't have come by conduction or convection, which need a material medium. It came as **radiation**.

Other examples: the warmth on your face from a fire, a heater's glowing coil, the hot bricks of a kiln; the heat from the coals of an open hearth that warms the whole room.

Radiation is the transfer of heat from one place to another in the form of electromagnetic waves, without needing any material medium. Radiation:

- travels through a **vacuum**, at the speed of light, 3×10^8 m/s;
- does **not heat the medium** it passes through (the air between you and a fire stays cool; the Sun's rays don't warm the air much on their way to the ground);
- travels in **straight lines**, so a screen between you and the fire cuts it off at once, and it casts shadows.

The energy given out by a hot body as radiation is **radiant energy** or **thermal radiation**. The word *radiation* is used both for the energy and for the process of sending it out.

Thermal radiation

Every body above absolute zero radiates energy all the time, as electromagnetic waves, just because of its temperature: an ice cube, your hand, the walls of the room. This is **thermal radiation**. A body that is hotter than its surroundings radiates more than it receives from them, and cools; one that is colder receives more than it gives out, and warms.

- How much a body radiates, and at which wavelengths, depends on its **temperature** and on the nature of its **surface**.
- At everyday temperatures, almost all thermal radiation is **infrared**, invisible to us, though our skin feels it as warmth. A body must reach about 500 °C before it gives out enough visible light to glow a dull red; hotter still, it glows orange, yellow, then white. The Sun, at about 5800 K, gives out most of its energy as visible light and near infrared.
- Thermal radiation is electromagnetic, like light, so it shows all the properties of light: it is **reflected**, **refracted**, shows **interference** and **diffraction**, and can be **polarized**.

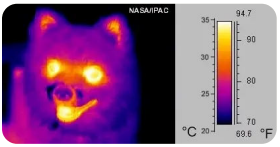


Figure 12.8 *A dog photographed in infrared, the thermal radiation it gives out. The camera shows warmer parts in brighter colors: the eyes and the inside of the mouth are warmest, the nose and the tips of the fur coldest. Every warm body glows like this, in light our eyes can't see.*
Photo: NASA/IPAC, Public domain

Radiation in daily life

a. **Electric heaters** have polished reflectors behind the glowing element, which reflect its radiation out into the room instead of letting the back of the heater absorb it.
b. **White clothes in summer, dark clothes in winter.** White cloth reflects most of the Sun's radiation and keeps you cooler; dark cloth absorbs it and warms you.
c. **Room radiators and hot-water pipes.** A pipe or radiator meant to heat a room is best dull and dark, so that it radiates well; pipes that carry hot water through cold places, where heat must not be lost, are lagged and covered in shiny foil.
d. **Thermometers and thermocouples** used to measure radiation have their bulb or junction blackened, so that they absorb as much of it as possible.
e. **Solar water heaters** on the roofs of Nepal have black tubes or plates to absorb the sunshine, behind glass that keeps the heat in.



Figure 12.9 *A solar water heater on a rooftop. Heaters like this are common on roofs in Kathmandu. The dark coating inside each glass tube absorbs sunlight; the vacuum between the tube's two glass walls stops the heat from escaping by conduction and convection, the same idea as a thermos flask.*
Photo: రవిచంద్ర, CC BY-SA 4.0

12.8 Reflection, transmission and absorption of heat radiation

When thermal radiation falls on a body, three things can happen to it: part is **reflected** from the surface, part is **absorbed** by the body (warming it), and the rest is **transmitted** through it (Figure 12.10).

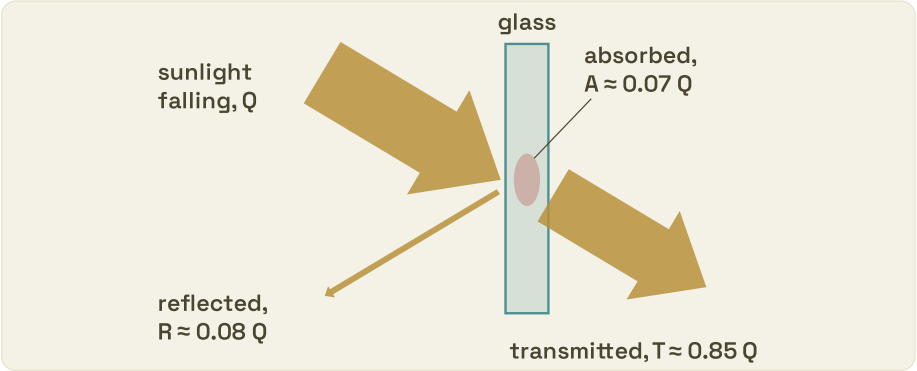


Figure 12.10 *Radiation of energy Q falls on a sheet. Part R is reflected from its surface, part A is absorbed inside it, and the rest T passes through. Here the widths of the arrows are drawn for ordinary window glass and sunlight: most is transmitted.*

Let Q be the energy of the radiation falling on the surface in a given time, and R, A and T the parts reflected, absorbed and transmitted. Energy is conserved, so

$$R + A + T = Q \tag{12.6}$$

Three ratios describe the surface:

1. **Reflectance** (coefficient of reflection) r: the ratio of the radiant energy reflected to the total falling on the surface in the same time, $r = \dfrac{R}{Q}$.
2. **Absorptance** (coefficient of absorption) a: the ratio of the radiant energy absorbed to the total falling on it, $a = \dfrac{A}{Q}$.
3. **Transmittance** (coefficient of transmission) t: the ratio of the radiant energy transmitted to the total falling on it, $t = \dfrac{T}{Q}$.

Dividing (12.6) by Q:

$$\frac{R}{Q} + \frac{A}{Q} + \frac{T}{Q} = 1 \quad \Rightarrow \quad r + a + t = 1 \tag{12.7}$$

The three fractions always add up to 1. Each lies between 0 and 1, and each depends on the material, its surface, its thickness and the wavelength of the radiation: window glass lets most visible light through, but hardly any of the long-wavelength infrared from warm bodies.

What (12.7) tells us:

a. **An opaque body** (one that transmits nothing, $t = 0$) has $r + a = 1$. The more it reflects, the less it absorbs: **a good reflector is a poor absorber**, and a poor reflector is a good absorber. A polished silver surface ($r \approx 0.97$) absorbs only about 3%; dull black soot ($r \approx 0.03$) absorbs about 97%.

b. **A perfectly black body** reflects nothing and transmits nothing ($r = 0$, $t = 0$), so $a = 1$: it absorbs all the radiation that falls on it. At room temperature such a body looks perfectly black, since no light comes back from it.

Check 5

A sheet transmits 10% and reflects 30% of the radiation falling on it. What fraction does it absorb?

a 0.30 b 0.60
c 0.70 d 0.90

Sample questions

12.9 Black body and black-body radiation

A **perfectly black body** is an ideal body that **absorbs all the radiation falling on it**, of every wavelength and from every direction, reflecting none and transmitting none ($a = 1$). At room temperature it would look perfectly black, since it sends back no light.

The same body is also the **best possible emitter**. Heated, a perfectly black body gives out radiation of **every wavelength**, more at each wavelength than any other body at the same temperature. Its radiation, **black-body radiation**, depends on nothing but its temperature. A good absorber is a good emitter (**Kirchhoff's law**, 1859: at the same temperature, a surface emits each wavelength in the same proportion as it absorbs it). A body that is a poor absorber, such as polished silver, is a poor emitter too.

"Black" describes how it absorbs, not how it looks when hot: a black body hot enough glows. A lump of charcoal looks black when cold and glows orange-red in a fire. The Sun's surface absorbs almost all radiation falling on it and radiates very nearly as a black body at about 5800 K, yet it is the brightest thing in our sky. Every body above absolute zero gives out thermal radiation: the stars, a hot stove, your own body, and even an ice cube.

Making a black body

No real surface is perfectly black. The nearest are **lamp black** (soot) and **platinum black**, which absorb about 96–98% of the radiation falling on them. A far better approach is a **cavity with a small hole**: radiation that enters through the hole bounces round inside, losing part of its energy at every bounce, and almost none of it ever finds its way back out. The hole behaves almost exactly as a perfectly black body. **Féry's black body** is made this way (Figure 12.11).

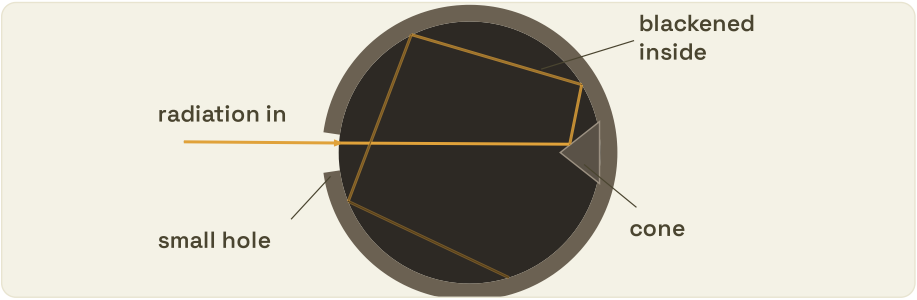


Figure 12.11 *Féry's black body: a hollow sphere, blackened with lamp black inside, with a small hole. A pointed cone opposite the hole stops a ray from bouncing straight back out. A ray that enters is absorbed a little at every bounce and is lost inside: the hole absorbs almost everything that falls on it.*

You can see the same effect at home: the pupil of your eye is a hole into a dark cavity, and so is the open window of a dark room seen from the street in daylight. Both look black, though the walls inside are not.

Emissive power and emissivity

The **emissive power** E of a body is the radiant energy it gives out per unit time, per unit area of its surface, at a given temperature:

$$E = \frac{\text{energy radiated}}{\text{area} \times \text{time}} = \frac{Q}{At} = \frac{P}{A}$$

where $P = Q/t$ is the power radiated. Its unit is the watt per square meter, W/m² (J/(s m²)).

The **emissivity** e of a surface is the ratio of its emissive power to that of a perfectly black body of the same size at the same temperature:

$$e = \frac{E}{E_{\text{black}}}$$

Emissivity is a ratio of two powers, so it has **no unit and no dimensions**. It depends on the nature of the surface and lies between 0 and 1:

- for a perfect reflector, $e = 0$: it radiates nothing;
- for an ordinary body, $0 < e < 1$ (polished aluminium about 0.05, red brick about 0.9, human skin about 0.97);
- for a perfectly black body, $e = 1$.

By Kirchhoff's law, a body's emissivity equals its absorptance: $e = a$.

CAREFUL

Black body or blackened body?

The word "black body" on its own usually means the ideal: $e = 1$, absorbing everything. A blackened surface such as soot is **nearly** black ($e \approx 0.97$). Any real body has $e < 1$.

Check 6

Which of these is the best absorber, and so also the best emitter, of thermal radiation?

a a polished silver cup
b a white-painted wall
c a pot coated with soot
d a mirror

12.10 Stefan's law of black-body radiation

In 1879 Josef Stefan found from experiments that the energy radiated by a body depends strongly on its temperature, and in 1884 Ludwig Boltzmann derived the same law from the theory of heat and electromagnetism. It is called **Stefan's law**, or the **Stefan–Boltzmann law**.

Stefan's law: the emissive power of a perfectly black body is directly proportional to the fourth power of its absolute temperature.

$$E \propto T^4 \qquad \Rightarrow \qquad E = \sigma T^4 \tag{12.8}$$

where T is the temperature of the body's surface **in kelvin** and σ (sigma) is **Stefan's constant**, the same for all black bodies:

$$\sigma = 5.67 \times 10^{-8}\ \text{W/(m}^2\ \text{K}^4\text{)}$$

Equation (12.8) is the energy the body gives out; it holds as written if the surroundings are at absolute zero, or if we count only what the body emits.

For a body that isn't perfectly black, of emissivity e, the emissive power is e times as much:

$$E = e\sigma T^4 \tag{12.9}$$

Since $E = \dfrac{Q}{At} = \dfrac{P}{A}$, the **total power radiated** by a surface of area A is

$$P = \frac{Q}{t} = eA\sigma T^4 \tag{12.10}$$

The fourth power makes radiation change dramatically with temperature: **double the absolute temperature, and a body radiates $2^4 = 16$ times as much**. A stove coil at 1300 K radiates about 350 times as much per square meter as a wall at room temperature, 300 K.

CAREFUL

Always kelvin

Stefan's law needs the **absolute** temperature. 27 °C is 300 K; 54 °C is 327 K, not 600 K. Doubling the Celsius temperature is not doubling T.

WORKED EXAMPLE

The power of a hot sphere

A sphere of radius 5 cm is at 127 °C and its surface has an emissivity of 0.6. Find the power it radiates. ($\sigma = 5.67 \times 10^{-8}$ W/(m² K⁴).)

Answer

$r = 5 \times 10^{-2}$ m, $T = 127 + 273 = 400$ K, $e = 0.6$.

Surface area: $A = 4\pi r^2 = 4\pi(5 \times 10^{-2})^2 = 3.14 \times 10^{-2}$ m².

$$P = eA\sigma T^4 = 0.6 \times 3.14 \times 10^{-2} \times 5.67 \times 10^{-8} \times (400)^4 = \mathbf{27.4\ W}$$

(This is what it gives out; it also takes in radiation from its surroundings, Section 12.11.)

Check 7

The absolute temperature of a black body is raised from 300 K to 900 K. Its emissive power becomes:

a 3 times as large
b 9 times as large
c 27 times as large
d 81 times as large

12.11 Net loss of heat by radiation

A body never radiates into nothing: its surroundings radiate too, and the body absorbs part of their radiation. A body at temperature T in surroundings at temperature T_0 (both in kelvin) gives out σT^4 per unit area and, if it is black, absorbs σT_0^4 per unit area from the surroundings. Its **net** emissive power, the rate at which it loses heat per unit area, is the difference:

$$E' = \sigma(T^4 - T_0^4) \tag{12.11}$$

and for a body of emissivity e (which also absorbs a fraction e of what falls on it):

$$E' = e\sigma(T^4 - T_0^4) \tag{12.12}$$

So the net power lost by radiation from a surface of area A is

$$P' = \frac{Q'}{t} = eA\sigma(T^4 - T_0^4) \tag{12.13}$$

If $T > T_0$, the body loses heat; if $T < T_0$, P' is negative: it gains heat from the warmer surroundings. If $T = T_0$, it radiates exactly as much as it receives, and its temperature doesn't change, though it is still radiating all the time.

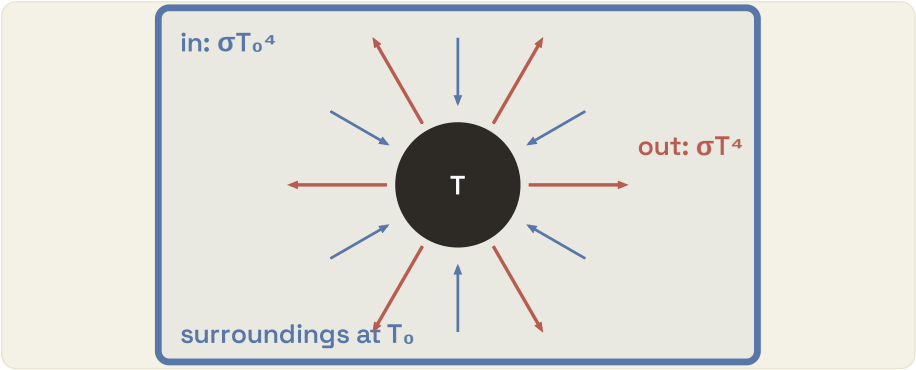


Figure 12.12 *A black body at T inside surroundings at T_0. It gives out radiation (σT^4 per unit area) and takes in the surroundings' radiation (σT_0^4); its net loss is the difference.*

WORKED EXAMPLE

Heat lost by a person

A person whose skin has a surface area of 2 m² sits in a room where the air and walls are at 20 °C. The skin is at 35 °C, and its emissivity is 0.97. Find the rate at which the person loses heat by radiation. ($\sigma = 5.67 \times 10^{-8}$ W/(m² K⁴).)

Answer

$T = 35 + 273 = 308$ K, $T_0 = 20 + 273 = 293$ K.

$$P' = eA\sigma(T^4 - T_0^4) = 0.97 \times 2 \times 5.67 \times 10^{-8} \times (308^4 - 293^4)$$

$308^4 = 9.00 \times 10^9$ and $293^4 = 7.37 \times 10^9$, so $308^4 - 293^4 = 1.63 \times 10^9$ K⁴.

$$P' = 1.10 \times 10^{-7} \times 1.63 \times 10^9 = \mathbf{179\ W}$$

That is more than the 100 W or so the body makes at rest: in a room at 20 °C, sitting bare-skinned, you lose heat faster than you make it, and you would soon feel cold. Clothes cut the loss by putting a cooler surface between your skin and the room.

12.12 Solar constant and the temperature of the Sun

The **solar constant** S is the energy of the Sun's radiation received per unit time, per unit area of a surface held at right angles to the rays, at the Earth's mean distance from the Sun (1 astronomical unit, AU), outside the atmosphere. Measured by satellites,

it is about

$$S = 1361 \text{ W/m}^2$$

(Some books round it to 1400 W/m².) Less reaches the ground: the atmosphere reflects and absorbs part, and on a clear noon in Nepal about 1000 W/m² arrives on a surface facing the Sun.

Together with Stefan's law, the solar constant gives the temperature of the Sun's surface, as Stefan himself did in 1879. Take the Sun as a perfectly black sphere of radius R and surface temperature T, at a distance r from the Earth (Figure 12.13).

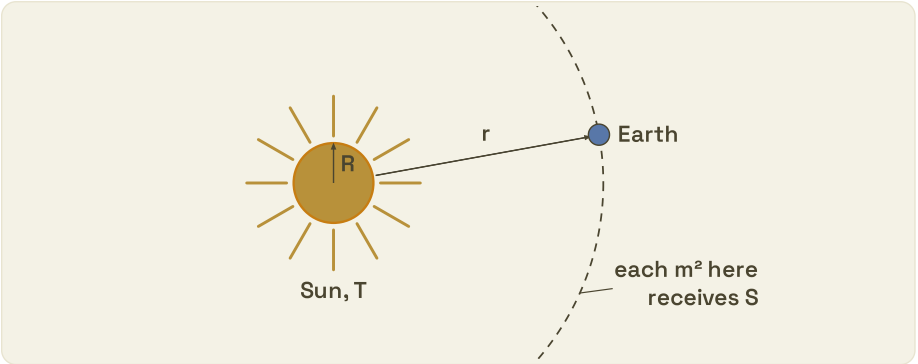


Figure 12.13 *The Sun, of radius R, radiates equally in all directions. All of its radiation crosses an imaginary sphere of radius r, the Earth's distance, where each square meter receives S. Not to scale: r is about 215 times R.*

1. By Stefan's law, each square meter of the Sun's surface gives out σT^4. Its whole surface, of area $4\pi R^2$, radiates the power
$$P = 4\pi R^2 \sigma T^4$$
2. This power spreads out equally in all directions. At the Earth's distance, all of it crosses an imaginary sphere of radius r, area $4\pi r^2$, each square meter of which receives S. So the power crossing that sphere is
$$P = 4\pi r^2 S$$
3. With nothing in between to absorb it (space is empty), the two are the same power:
$$4\pi R^2 \sigma T^4 = 4\pi r^2 S \quad \Rightarrow \quad T^4 = \frac{S}{\sigma}\left(\frac{r}{R}\right)^2$$
$$\boxed{T = \left[\frac{S}{\sigma}\left(\frac{r}{R}\right)^2\right]^{1/4}} \tag{12.14}$$

With today's values ($S = 1361$ W/m², $r = 1.496 \times 10^{11}$ m, $R = 6.96 \times 10^8$ m), this gives about **5770 K**, or about 5800 K. It is called the Sun's **effective** (or apparent) temperature: the temperature of a black body of the Sun's size that would give out the same power.

WORKED EXAMPLE

The temperature of the Sun

Find the temperature of the Sun's surface, given its radius 7.04×10^5 km, its distance from the Earth 14.72×10^7 km, the solar constant 1400 W/m², and Stefan's constant 5.7×10^{-8} W/(m² K⁴).

Answer

$R = 7.04 \times 10^5 \text{ km} = 7.04 \times 10^8 \text{ m}$; $r = 14.72 \times 10^7 \text{ km} = 14.72 \times 10^{10} \text{ m}$.

$$\frac{r}{R} = \frac{14.72 \times 10^{10}}{7.04 \times 10^8} = 209.1$$

$$T^4 = \frac{S}{\sigma}\left(\frac{r}{R}\right)^2 = \frac{1400}{5.7 \times 10^{-8}} \times 209.1^2 = 2.456 \times 10^{10} \times 4.372 \times 10^4 = 1.074 \times 10^{15} \text{ K}^4$$

$$T = (1.074 \times 10^{15})^{1/4} = \mathbf{5724\ K}$$

DID YOU KNOW?

Feeling the Sun's power

At noon on a clear day, about 1000 W falls on each square meter of ground facing the Sun in Nepal, as much as a heater. A roof of 50 m² catches 50 kW, more than a whole house uses. A solar panel turns about a fifth of it into electricity; a black solar-heater tube turns most of it into hot water.

IN SHORT

Key ideas of Unit 12

- Heat flows from hot to cold by **conduction** (particle to particle, and free electrons in metals; needs a medium), **convection** (bulk movement of a fluid; natural convection needs gravity), and **radiation** (electromagnetic waves; no medium needed).
- Temperature gradient $d\theta/dx$ (K/m). Along a lagged rod in the steady state it is uniform, $(\theta_1 - \theta_2)/l$; along an unlagged rod the temperature falls along a curve.
- Conduction: $\dfrac{Q}{t} = kA\,\dfrac{\theta_1 - \theta_2}{x}$; k in W/(m K), dimensions [MLT^{-3}K^{-1}]. In layers, the same heat flows through each layer.
- Searle's method (good conductors): $k = \dfrac{ms(\theta_3 - \theta_4)x}{At(\theta_1 - \theta_2)}$, at the steady state.
- Convection: $\dfrac{Q}{t} = hA\,\Delta\theta$. Sea and land breezes, trade winds, monsoons, chimneys and ventilators.
- $r + a + t = 1$; a good absorber is a good emitter and a poor reflector. A perfectly black body has $a = e = 1$.
- Stefan's law: $E = \sigma T^4$, $P = eA\sigma T^4$, $\sigma = 5.67 \times 10^{-8}$ W/(m² K⁴), T in kelvin. Net loss: $P' = eA\sigma(T^4 - T_0^4)$.
- Sun's temperature: $T = \left[\dfrac{S}{\sigma}\left(\dfrac{r}{R}\right)^2\right]^{1/4} \approx 5800$ K, with $S \approx 1361$ W/m².

Exercise

Choose the correct option

Check 8

1. Which of these ways of transferring heat depends on gravity?

a convection
b conduction
c radiation
d conduction and convection

Check 9

2. Which of the following has no effect on the heat radiated (given out) by a surface?

a the temperature of the surroundings
b the area of the surface
c the nature of the surface
d the temperature of the surface

Check 10

3. The total radiation given out by a perfectly black body is proportional to:

a its absolute temperature
b the square of its absolute temperature
c the cube of its absolute temperature
d the fourth power of its absolute temperature

Check 11

4. The thermal conductivity of a material depends on:

a its area of cross-section
b the temperature difference across it
c the nature of the material
d nothing: it is not a real effect

Check 12

5. A good absorber of radiation is also:

a a good reflector
b a good transmitter
c a bad emitter
d a good emitter

Check 13

6. If the absolute temperature of a black body is doubled, the rate at which it radiates heat increases by a factor of:

a 2
b 4
c 8
d 16

Check 14

7. At which of these temperatures does a black body not radiate heat?

a 0 °C
b 0 K
c 273 °C
d 273 K

Check 15

8. The rate of flow of heat in the steady state through a metal bar of cross-section 1 m^2, kept at a temperature gradient of 1 °C/m, is:

a its thermal conductivity
b Stefan's constant
c its specific heat capacity
d the solar constant

Check 16

9. At the same distance from a fire, why is it hotter above it than beside it?

a Heat radiates only upward.
b Air radiates heat upward.
c Convection carries much more heat upward.
d All the processes conduct heat upward.

Check 17

10. A solid sphere and a hollow sphere of the same material and the same size are heated to the same temperature and left to cool in the same surroundings. Which is correct?

a The hollow one cools faster.
b The solid one cools faster.
c Both cool at the same rate.
d There is not enough information.

Check 18

11. Heat flows through two cylinders of the same material. The ratio of their diameters is 1 : 2 and of their lengths 2 : 1. If the temperature difference between their ends is the same, the ratio of the heat conducted through them per unit time is:

a 1 : 8
b 1 : 4
c 8 : 1
d 2 : 7

Check 19

12. A rod AB is 150 cm long. End A is kept at 100 °C and end B at 25 °C. What is the temperature of a point P 50 cm from end B? (Assume the rod is lagged.)

a 50 °C
b 60 °C
c 75 °C
d 80 °C

Check 20

13. A wall has two layers, A and B, of different materials and the same thickness. The thermal conductivity of A is one-third of B's. If the temperature difference across layer B is 15 °C, what is the temperature difference across layer A?

a 5 °C
b 20 °C
c 45 °C
d 60 °C

Check 21

14. Four objects of the same size and material, painted blue, red, black and white, are heated together and then left to cool. Which cools first?

a blue
b red
c black
d white

Answer these questions

15.

a. On a winter night you feel warmer when clouds cover the sky than when it is clear. Why?

b. The bulbs of two identical thermometers are coated, one with lamp black and the other with silver. Compare their readings when they are exposed i. to a hot sunny day, ii. to a clear night sky.

c. You can hold your fingers beside a candle flame without harm, but not above it. Why?

16.

a. At a wedding party on a cold winter evening you are asked to sit on a chair. Would you choose a metal chair or a wooden chair? Explain.

b. It is well known that a potato bakes faster if a large nail is pushed through it. Why?

c. Is an aluminium nail better than a steel nail for baking a potato? Give a reason.

d. A newly made quilt is warmer than an old one. Why?

e. A pot with a steel bottom 8.5 mm thick rests on a hot stove. The area of the bottom is 0.15 m^2. The water inside is at 100 °C, and 390 g of water evaporates every 3 minutes. Find the temperature of the bottom surface of the pot, in contact with the stove. (Thermal conductivity of steel 50.2 W/(m K); specific latent heat of vaporization of water 2.256×10^6 J/kg.)

18.

a. How does tea in a thermos flask stay hot for a long time?

b. Why are ice houses in the Arctic (igloos) often made with double walls?

c. Estimate the rate of heat loss through a glass window of area 2.0 m^2 and thickness 3.0 mm, when the room is at 20 °C and the air outside at 5 °C. (Thermal conductivity of glass 1.2 W/(m K); take the faces of the glass to be at the temperatures of the air on each side.)

d. A squirrel wraps its bushy tail round its body during its winter sleep. Why?

19.

a. The Earth constantly receives heat radiation from the Sun and is warmed by it. Why doesn't the Earth become as hot as the Sun?

b. Does a body at 25 °C radiate heat in a room at 35 °C? If it does, why doesn't its temperature fall?

c. Standing in the sun on a cold winter day is much more pleasant than standing in the shade. Is the air in the sun much warmer than the air in the shade?

d. The element of a 1 kW electric fire has a surface area of 0.006 m^2. Estimate its working temperature, taking it as a black body and neglecting the radiation it receives. ($\sigma = 5.7 \times 10^{-8}$ W/(m^2 K^4).)

20.

a. We are lucky that the Earth is not in thermal equilibrium with the Sun, whose surface is at about 5800 K. Why are they not in thermal equilibrium?

b. How do glasshouses help us keep plants warm?

c. A sphere of radius 2.00 cm with a black surface is cooled and then hung in a large evacuated enclosure whose black walls are kept at 27 °C. When the sphere's temperature is −73 °C, its thermal energy is increasing at 1.85 J/s. Calculate a value for Stefan's constant.

d. Why are petrol tanks usually painted with aluminium paint?

21.

a. Why are stainless-steel cooking pans often made with an extra copper bottom?

b. What special properties should a cooking pot have?

c. A metal rod 20 cm long, of cross-section 3.14 cm^2, is covered with a non-conducting material. One end is kept at 100 °C and the other end in ice at 0 °C. 25 g of ice melts in 5 minutes. Calculate the thermal conductivity of the metal. (Specific latent heat of fusion of ice 3.36×10^5 J/kg.)

22. A black body of surface area 10^{-4} m^2 is heated to a high temperature and placed in an enclosure kept at 300 K. It radiates heat to the enclosure at a net rate of 0.73 W. What is the temperature of the black body? ($\sigma = 6 \times 10^{-8}$ W/(m^2 K^4).)

23. Each square meter of the Earth's surface facing the Sun receives energy from the Sun at the rate of 1400 J/s. The distance of the Earth from the center of the Sun is 1.5×10^{11} m, and the Sun's radius is 7×10^8 m. Taking the Sun as a perfect black body, find the temperature of its surface. ($\sigma = 5.67 \times 10^{-8}$ W/(m^2 K^4).)

A companion to your textbook, not a replacement for it: study from the book your school uses, and where the two differ, follow your teacher. Found a mistake? Please tell us.