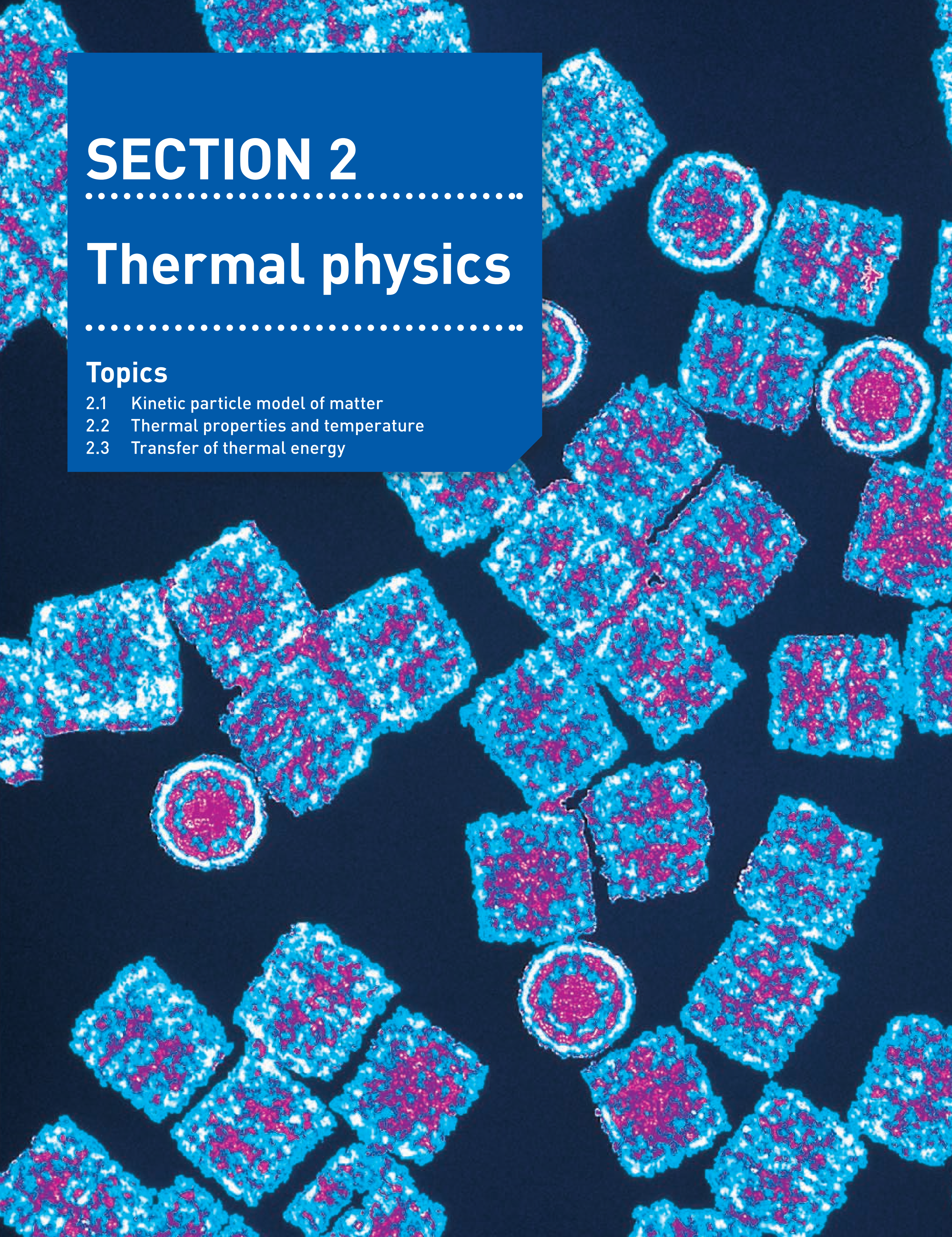


SECTION 2

Thermal physics

Topics

2.1 Kinetic particle model of matter
2.2 Thermal properties and temperature
2.3 Transfer of thermal energy

2.1 Kinetic particle model of matter

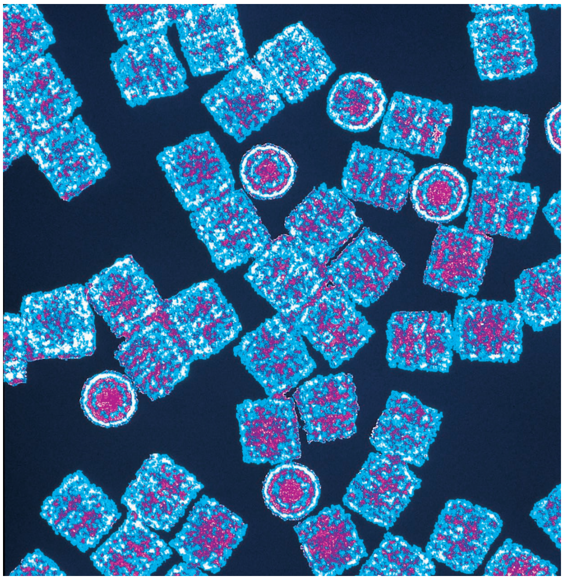
2.1.1 States of matter

FOCUS POINTS

★ Know the properties of solids, liquids and gases.
★ Understand that changes in state can occur and know the terms to describe these changes.

In this topic you will learn about the three states of matter: solids, liquids and gases. The particles in each are ordered differently and this leads to each state having different properties. You will find that solids have a high level of internal order, a liquid has less, and in a gas the particles have no order and move about randomly. The state of a material can be altered by heating or cooling. In a solid the bonds between particles break down on heating and it melts into a liquid; for example, ice melts into water. Boiling a liquid produces a gas with well separated particles; water turns into steam. The three states of matter can be represented in a particle diagram.

Matter is made up of tiny particles (atoms, **molecules**, ions and electrons) which are too small for us to see directly. But they can be 'seen' by scientific 'eyes'. One of these is the electron microscope. Figure 2.1.1 is a photograph taken with such an instrument, showing molecules of a protein. Molecules consist of even smaller particles called **atoms** and these are in continuous motion.



▲ **Figure 2.1.1** Protein molecules

Properties of solids, liquids and gases

Matter can exist in different states and each state has different characteristics.

Solids

Solids have a definite shape and volume and are not easily compressed. The particles in a solid are close together and in fixed positions.

When a force is applied to a solid the atoms move slightly further apart in the direction of the force and stretching occurs (see Topic 1.5.1). When a solid is heated (see Topic 2.2), the distance between atoms increases. If enough energy is supplied to the solid the atoms move even further apart and **melting** into a liquid occurs.

Liquids

Liquids have a definite volume but their shape depends on the container they are kept in. They are more easily compressed or stretched than solids and also expand more when heat is applied. The particles in a liquid are further apart than they are in a solid and have a less ordered structure. They are not fixed in position and can slide over each other when the liquid is poured. The liquid then takes on the shape of the new container.

When a liquid is cooled sufficiently, *solidification* occurs and it returns to the solid state. The density of a material in its solid state is usually higher than it is in its liquid state. When a liquid is heated, particles can escape from its surface by a process called **evaporation**. When sufficient energy is supplied to the liquid, **boiling** occurs and the liquid turns into a gas.

Gases

Gases have no definite shape or volume as these depend on the dimensions of the container. The particles in a gas are much further apart than they are in a liquid and the density of a gas is much lower than that of a liquid. The particles have no ordered structure and are able to move about freely in a random manner. Gases are more easily compressed than solids or liquids and expand more when they are heated. When a gas is cooled sufficiently it will return to the liquid state in a process known as **condensation**.

Drops of water are formed when steam condenses on a cold window pane, for example.

Test yourself

1 Using what you know about the compressibility (squeezability) of the different states of matter, explain why
  a air is used to inflate tyres
  b steel is used to make railway lines.
2 Identify the processes in which
  a a solid turns into a liquid
  b a liquid turns into a gas
  c a liquid turns into a solid
  d a gas turns into a liquid.

2.1.2 Particle model

FOCUS POINTS

- ★ Describe the particle structures of solids, liquids and gases and represent these states using particle diagrams.
- ★ Understand how temperature affects the movement of particles.
- ★ Understand the factors that affect the properties of solids, liquids and gases.
- ★ Understand the relationship between the kinetic energy of particles and temperature, including the concept of absolute zero.
- ★ Know how a change in pressure in a gas affects the motion and number of collisions of its particles.
- ★ Describe how a change in pressure of a gas affects the forces exerted by particles colliding with surfaces (force per unit area).

The properties of solids, liquids and gases can be related to the arrangement, separation and motion of the particles in each. In the previous section, you learnt about the properties of solids, liquids and gases. In this topic, you will learn that in a gas, the particles are well separated and in constant random motion, producing pressure on a container by their collisions with its surfaces. In a solid, the particles are closely arranged and firmly bound together, with a regular pattern in crystals. In a liquid the particles are further apart, with only local ordering between particles that have more freedom of movement than those in a solid.

Particle model of matter

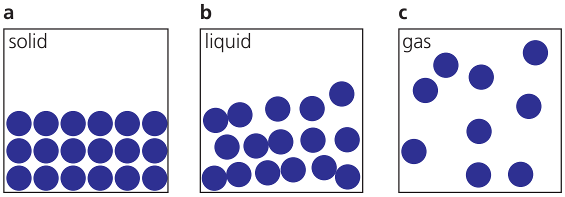
As well as being in continuous motion, particles (atoms, molecules, ions and electrons) also exert strong electric forces on one another when they are close together. The forces are both attractive and repulsive. The former hold particles together and the latter cause matter to resist compression.

The **particle model** can explain the existence of the solid, liquid and gaseous states.

Solids

Structure

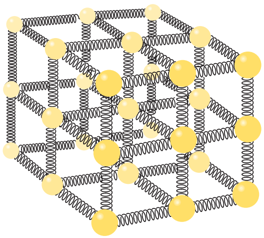
In solids the particles are close together and the attractive and repulsive forces between neighbouring molecules balance. Also, each particle vibrates about a fixed position. Particles in a solid can be arranged in a regular, repeating pattern like those formed by crystalline substances. Figure 2.1.2a represents the arrangement of particles in a solid.



▲ **Figure 2.1.2** Arrangements of particles in a solid, liquid and gas

Properties

We can imagine springs (Figure 2.1.3) representing the electric forces between particles that hold them together and determine the forces and distances between them. These forces enable the solid to keep a definite shape and volume, while still allowing the individual particles to vibrate backwards and forwards. Owing to the strong forces between particles, solids resist compression and expand very little when heated.



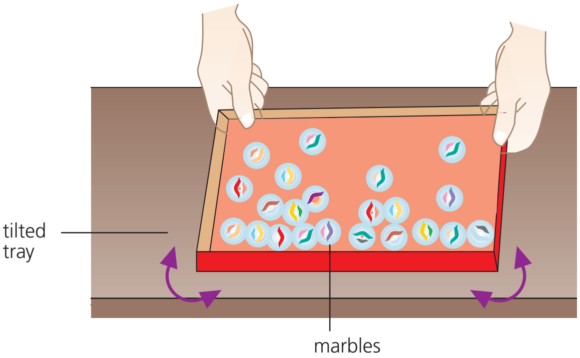
▲ **Figure 2.1.3** The electric forces between particles in a solid can be represented by springs.

Liquids

Structure

In liquids the particles are slightly further apart than in solids but still close enough together to have a definite volume (Figure 2.1.2b). As well as vibrating, they can at the same time move rapidly over short distances, slipping past each other in all directions.

A model to represent the liquid state can be made by covering about a third of a tilted tray with marbles ('particles') (Figure 2.1.4). It is then shaken back and forth and the motion of the marbles observed. The marbles are able to move around but most stay in the lower half of the tray, so the liquid has a fairly definite volume. A few energetic marbles escape from the 'liquid' into the space above. They represent particles that have evaporated from the liquid surface and become gas or vapour particles. The thinning out of the marbles near the liquid surface can also be seen.



▲ **Figure 2.1.4** A model of particle behaviour in a liquid

Properties

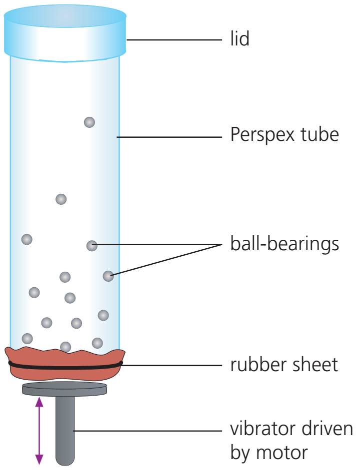
In a liquid the forces between particles are less than in a solid and so the distance between particles is greater. Liquids have a definite volume but individual particles can slide over each other and are never near another particle long enough to get trapped in a regular pattern. This allows liquids to flow and take on the shape of the vessel containing them. The forces between particles are strong enough that liquids are only slightly more easily compressed than solids. When heated, the particles move further apart, enabling liquids to expand more easily than solids. As the temperature increases some particles may have sufficient energy to escape from the surface of the liquid, resulting in evaporation of the liquid.

Gases

Structure

The particles in gases are much further apart than in solids or liquids (about ten times; see Figure 2.1.2c) and so gases are much less dense and can be squeezed (compressed) into a smaller space. The particles dash around at very high speed (about 500 m/s for air molecules at 0°C) in all the space available. It is only during the brief spells when they collide with other particles or with the surfaces of the container that the particle forces act.

A model of a gas is shown in Figure 2.1.5. The faster the vibrator works, the more often the ball-bearings have collisions with the lid, the tube and with each other, representing a gas at a higher temperature. Adding more ball-bearings is like pumping more air into a tyre; it increases the pressure. If a polystyrene ball (1 cm diameter) is dropped into the tube, its irregular motion is similar to the random way smoke particles behave in air; an observation that provides evidence for the kinetic particle model of matter.



▲ **Figure 2.1.5** A model of particle behaviour in a gas

Properties

Owing to the high speed and the large distance between particles in a gas the interaction between them is small. Gases have no shape and their volume is determined by the volume of the container. They are easily compressed, and expand much more than solids or liquids when heated.

Temperature and kinetic energy

In a solid at room temperature, the particles vibrate about fixed positions. When energy is supplied to the solid and its temperature increases, the particles vibrate more strongly and the average kinetic energy of the particles increases. When the temperature is reduced, the average kinetic energy of the particles reduces, and eventually a temperature is reached where particle motion ceases and the kinetic energy of the particles is zero. We call this temperature **absolute zero** and it occurs at −273°C.

Pressure and kinetic energy

The particle model can explain the behaviour of gases.

Gas pressure

All the particles in a gas are in rapid random motion, with a wide range of speeds, and repeatedly hit and rebound from the surfaces of the container in huge numbers per second.

This causes a force at right angles to the surfaces of the container or a pressure. When the temperature of the gas rises, so does the average speed and kinetic energy of the particles. Collisions with the surfaces of the container occur more frequently and so the pressure of the gas increases.

Force and gas pressure

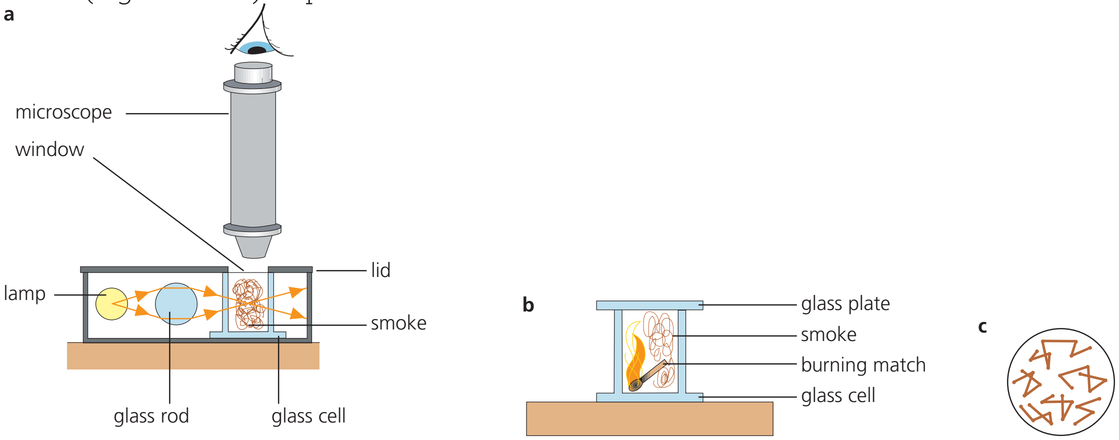
At each collision of a gas particle with a surface of the container, it undergoes a change of momentum which produces a force on the surface (see Topic 1.6). At a constant temperature the average force and hence the pressure exerted on the surface is constant, since pressure is force per unit area. When the temperature rises, the average speed of the particles increases, and the change of momentum in collisions with the surfaces of the container increases so that the average force and hence the gas pressure increases.

Going further

Practical work

Brownian motion

The apparatus is shown in Figure 2.1.6a. First fill the glass cell with smoke using a match (Figure 2.1.6b). Replace the lid on the apparatus and set it on the microscope platform. Connect the lamp to a 12 V supply; the glass rod acts as a lens and focuses light on the smoke.



▲ **Figure 2.1.6**

Carefully adjust the microscope until you see bright specks dancing around haphazardly (Figure 2.1.6c). The specks are smoke particles seen by reflected light; their random motion is called Brownian motion and is evidence for the kinetic particle model of matter. This motion is due to collisions between the microscopic particles in a suspension and the particles of the gas or liquid.

1. What are the specks of light in the glass cell of the Brownian motion experiment?
2. In a glass cell set up to show Brownian motion, describe how the specks of light move.
3. What do you think might cause microscopic particles to move in the way they do in a Brownian motion experiment?

Explanation of Brownian motion

The random motion of the microscopic smoke particles in the cell in Figure 2.1.6 is due to random molecular collisions of fast-moving air molecules in the cell. A smoke particle is massive compared with an air molecule, but if there are more high-speed molecules striking one side of it than the other at a given instant, the particle will move in the direction in which there is a net force. The imbalance, and hence the direction of the net force, changes rapidly in a random manner.

Test yourself

3 Explain the structure of
  a solids
  b liquids
  c gases.
  in terms of the particle model.
4 Explain what is meant by the term absolute zero.

2.1.3 Gases and the absolute scale of temperature

FOCUS POINTS

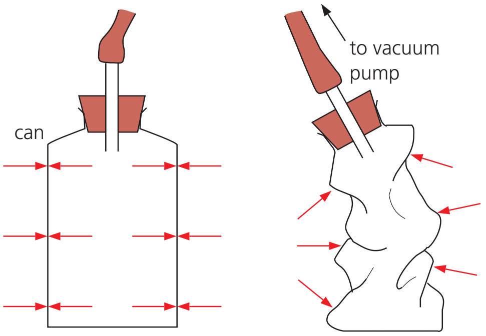
- ★ Describe, in terms of particles, the effect of change of temperature or volume on the pressure of a fixed mass of gas, and the effect of temperature on volume at constant pressure.
- ★ Use the correct equation to calculate pressure and volume of a fixed mass of gas, and be able to represent this relationship graphically.
- ★ Convert temperatures between the Celsius and Kelvin temperature scales using the correct equation.

Gases show the simplest behaviour of the three states of matter and respond to changes of temperature or volume by a change of pressure. By keeping either volume or temperature constant in an experiment, their relationships with pressure can be determined and explained in terms of the kinetic particle model of matter. The properties of gases can be exploited for use in thermometers to measure temperature. You will be familiar with the Celsius scale of temperature for everyday measurements; the freezing temperature of water is set at 0°C and the boiling temperature of water at 100°C. In both the Kelvin and Celsius temperature scales, there are 100 degrees between the freezing temperature and boiling temperature of water, but the Kelvin scale starts from –273°C where the motion of particles ceases.

Pressure of a gas

The air forming the Earth's atmosphere stretches upwards a long way. Air has weight; the air in a normal room weighs about the same as you do, about 500 N. Because of its weight the atmosphere exerts a large pressure at sea level, about 100 000 N/m^2 = 10^5 Pa (or 100 kPa). This **atmospheric pressure** acts equally in all directions.

A gas in a container exerts a pressure on the surfaces of the container. If air is removed from a can by a vacuum pump (Figure 2.1.7), the can collapses because the air pressure outside is greater than that inside. A space from which all the air has been removed is a **vacuum**. Alternatively, the pressure in a container can be increased, for example by pumping more gas into the can; a Bourdon gauge (Topic 1.8) is used for measuring gas pressures.



▲ **Figure 2.1.7** Atmospheric pressure collapses the evacuated can.

When a gas is heated, as air is in a jet engine, its pressure as well as its volume may change. To study the effect of temperature on these two quantities we must keep one fixed while the other is changed. When investigating relationships between properties only one **variable** should be changed at a time.

Effect on pressure of a change in temperature (constant volume)

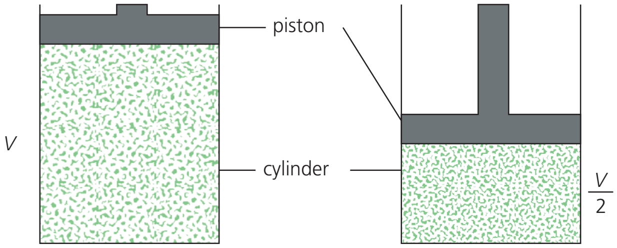
When a gas is heated and its temperature rises, the average speed of its particles increases. If the volume of a fixed mass of gas stays constant, its pressure increases because the change of momentum per second when the particles collide with the surfaces increases, leading to a larger force per unit area and hence pressure.

Effect on volume of temperature (constant pressure)

The particles in a gas are free to move about rapidly and fill the entire volume of the container. When a gas is heated and its temperature rises, the average speed of its particles increases; this means that there are more frequent collisions with the surfaces of the container and a hit by a molecule produces a larger force on the walls. If the pressure of the gas is to remain constant, the volume of the container must increase so that the frequency of collisions decreases; that means expansion of the gas must occur. See Practical work p. 95.

Effect on pressure of a change in volume (constant temperature)

If the volume of a fixed mass of gas is halved by halving the volume of the container (Figure 2.1.8), the number of particles per cm^3 will be doubled. There will be twice as many collisions per second with the surfaces, i.e. the pressure is doubled.



▲ **Figure 2.1.8** Halving the volume doubles the pressure.

Practical work

Effect on pressure of temperature (volume constant)

Safety

- Eye protection must be worn.
- The Bourdon gauge should be firmly clamped to prevent toppling.
- Take care with hot apparatus.

The apparatus is shown in Figure 2.1.9. The rubber tubing from the flask to the pressure gauge should be as short as possible. The flask must be in water almost to the top of its neck and be securely clamped to keep it off the bottom of the can. The water is heated either by standing the can on a hot plate or on a tripod over a Bunsen burner.

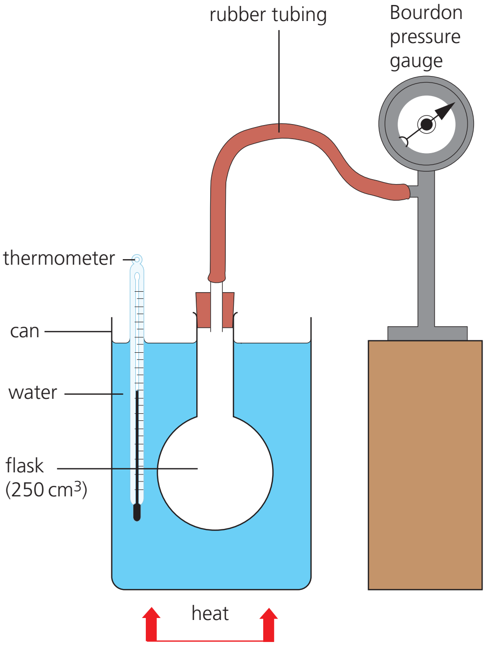
Record the pressure over a wide range of temperatures, but before taking a reading from the **thermometer**, stop heating, stir and allow time for the gauge reading to become steady; the air in the flask will then be at the temperature of the water. Take about six readings and tabulate the results.

Plot a graph of pressure on the y-axis and temperature on the x-axis.

4 **a** Name the independent variable in the experiment.
  b Name the dependent variable.

5 Why must the volume be kept constant in the experiment?

6 What precautions should you take to obtain accurate results in the experiment?



▲ **Figure 2.1.9**

Effect on volume of pressure (temperature constant)

Changes in the volume of a gas due to pressure changes can be studied using the apparatus in Figure 2.1.10. The volume V of air trapped in the glass tube is read off on the scale behind. The pressure is altered by pumping air from a foot pump into the space above the oil reservoir. This forces more oil into the glass tube and increases the pressure p on the air in it; p is measured by the Bourdon gauge. Take about six different measurements. Plot a graph of pressure versus volume as shown in Figure 2.1.11a.

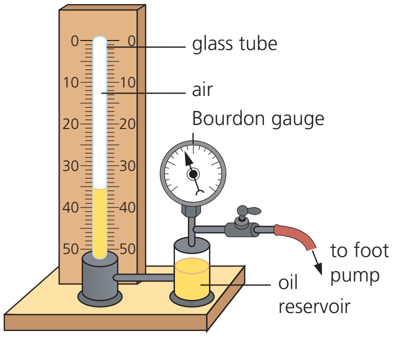


Figure 2.1.10

7 a Name the independent variable in the experiment.

b Name the dependent variable.

8 A graph of pressure against 1/volume for the results of the experiment is shown in Figure 2.1.11b. Name the features of the graph which suggest that pressure is proportional to 1/volume.

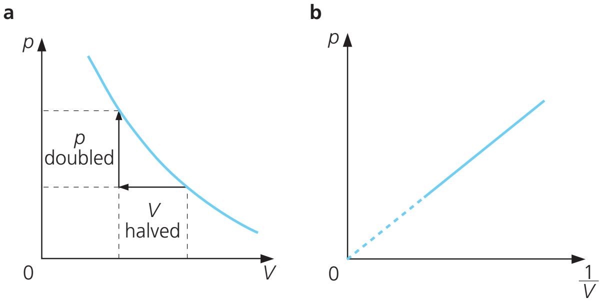


Figure 2.1.11

Variations in gas pressure with volume

The variation of the pressure of a fixed mass of gas with changes in volume (at constant temperature) is shown in Figure 2.1.11a. Close examination of the curve shows that if p is doubled, V is halved. That is, *p is inversely proportional to V*. In symbols

$$p \propto \frac{1}{V} \text{ or } p = \text{constant} \times \frac{1}{V}$$

$$\therefore \quad pV = \text{constant}$$

If several pairs of readings, p_1 and V_1, p_2 and V_2, etc. are taken, then it can be confirmed that

$$p_1V_1 = p_2V_2 = \text{constant}$$

This is Boyle's law, which is stated as follows:

> The pressure of a fixed mass of gas is inversely proportional to its volume if its temperature is kept constant.

Since p is inversely proportional to V, then p is directly proportional to $1/V$. A graph of p against $1/V$ is therefore a straight line through the origin (Figure 2.1.11b).

Worked example

A certain quantity of gas has a volume of 40 cm^3 at a pressure of 1×10^5 Pa. Find its volume when the pressure is 2×10^5 Pa. Assume the temperature remains constant.

Using the equation pV = constant we have

$$p_1V_1 = p_2V_2$$

Rearranging the equation gives

$$V_2 = p_1 \times V_1/p_2$$

$$= 1 \times 10^5\,\text{Pa} \times 40\,\text{cm}^3/2 \times 10^5\,\text{Pa}$$

$$= 20\,\text{cm}^3$$

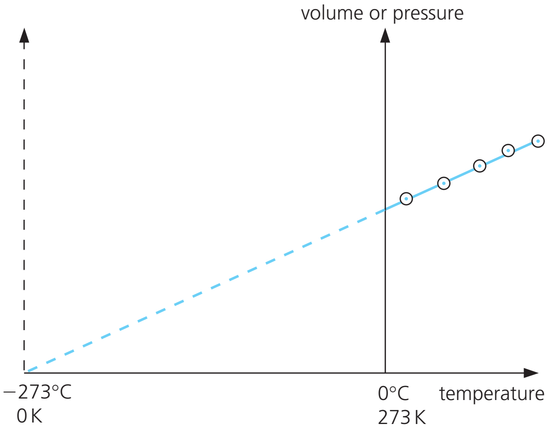
Now put this into practice

1 A fixed mass of gas has a volume of 9 cm^3 at a pressure of 1×10^5 Pa. Find its volume when the pressure is 3×10^5 Pa.

2 A certain quantity of gas has a volume of 40 cm^3 at a pressure of 2×10^5 Pa. Find its pressure when the volume is 20 cm^3.

Celsius and Kelvin temperature scales

The volume–temperature and pressure–temperature graphs for a gas are straight lines (Figure 2.1.12). They show that gases expand **linearly** with temperature as measured on a mercury thermometer, i.e. equal temperature increases cause equal volume or pressure increases.



▲ **Figure 2.1.12**

The graphs do not pass through the Celsius temperature origin (0°C). If graph lines are extrapolated backwards, they cut the temperature axis at about −273°C. This temperature is called absolute zero because we believe it is the lowest temperature possible. It is the zero of the *absolute* or *Kelvin scale of temperature*. At absolute zero molecular motion ceases and a substance has no internal energy.

Degrees on this scale are called **kelvins** and are denoted by K. They are exactly the same size as Celsius degrees. Since −273°C = 0 K, conversions from °C to K are made by adding 273. For example

$$0°\text{C} = 273\,\text{K}$$

$$15°\text{C} = 273 + 15 = 288\,\text{K}$$

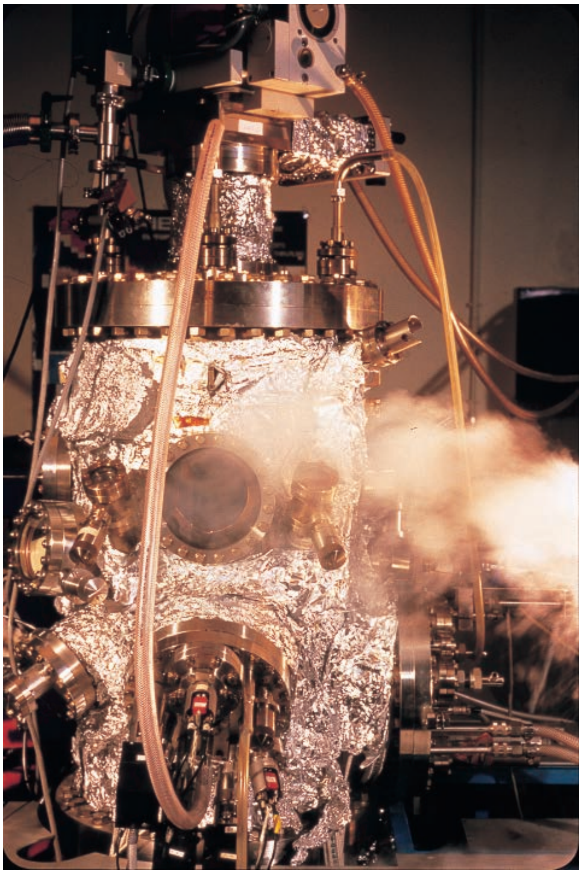
$$100°\text{C} = 273 + 100 = 373\,\text{K}$$

Kelvin or absolute temperatures are represented by the letter *T*, and if θ (Greek letter 'theta') stands for a **degrees Celsius** scale temperature then, in general,

$$T = 273 + \theta$$

Near absolute zero strange things occur. Liquid helium becomes a superfluid. It cannot be kept in an open vessel because it flows up the inside of the vessel, over the edge and down the outside.

Some metals and compounds become superconductors of electricity and a **current**, once started in them, flows forever, without a battery. Figure 2.1.13 shows research equipment that is being used to create materials that are superconductors at very much higher temperatures, such as −23°C.



▲ **Figure 2.1.13** This equipment is being used to make films of complex composite materials that are superconducting at temperatures far above absolute zero.

? Worked example

a Convert 27°C to K.
Substitute in the equation $T = 273 + \theta$ to give

$$T = 273 + 27 = 300\,\text{K}$$

b Convert 60 K to °C.
Rearrange the equation $T = 273 + \theta$ to give

$$\theta = T - 273 = 60 - 273 = -213°\text{C}$$

Now put this into practice

1 Convert 80°C to K.
2 Convert 100 K to °C.

Practical work

Effect on volume of temperature (pressure constant): Charles' law

Safety

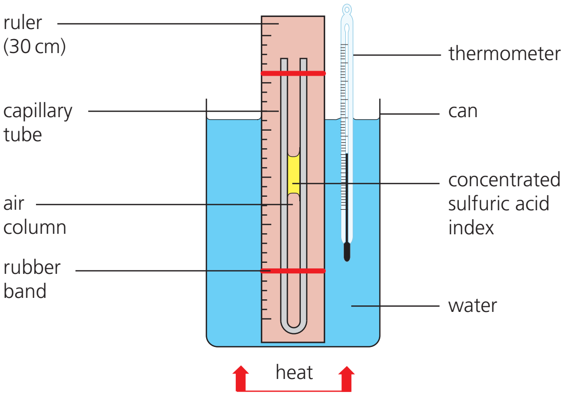
- Eye protection must be worn.
- Take care as concentrated sulfuric acid is highly corrosive. Do not touch it if any leaks out of the tube.

Arrange the apparatus as in Figure 2.1.14. The index of concentrated sulfuric acid traps the air column to be investigated and also dries it. Adjust the capillary tube so that the bottom of the air column is opposite a convenient mark on the ruler.

Note the length of the air column (between the lower end of the index and the sealed end of the capillary tube) at different temperatures but, before taking a reading, stop heating and stir well to make sure that the air has reached the temperature of the water. Put the results in a table.

Plot a graph of volume (in cm, since the length of the air column is a measure of it) on the *y*-axis and temperature (in °C) on the *x*-axis.

The pressure of (and on) the air column is constant and equals atmospheric pressure plus the pressure of the acid index.



▲ **Figure 2.1.14**

9 **a** Name the independent variable in the experiment.
b Name the dependent variable.

10 The results of the experiment are plotted in a graph of volume versus temperature and appear similar to those shown in Figure 2.1.12. What do the results indicate about the relationship between volume and temperature?

Going further

The gas laws

Using absolute temperatures, the gas laws can be stated in a convenient form for calculations.

Charles' law

In Figure 2.1.12 the volume–temperature graph passes through the origin if temperatures are measured on the Kelvin scale, that is, if we take 0 K as the origin. We can then say that the volume V is directly proportional to the absolute temperature T, i.e. doubling T doubles V, etc. Therefore

$$V \propto T \text{ or } V = \text{constant} \times T$$

or

$$\frac{V}{T} = \text{constant} \quad (1)$$

Charles' law may be stated as follows.

> The volume of a fixed mass of gas is directly proportional to its absolute temperature if the pressure is kept constant.

Pressure law

From Figure 2.1.12 we can say similarly for the pressure p that

$$p \propto T \text{ or } p = \text{constant} \times T$$

or

$$\frac{p}{T} = \text{constant} \quad (2)$$

The pressure law may be stated as follows.

> The pressure of a fixed mass of gas is directly proportional to its absolute temperature if the volume is kept constant.

Variations in gas pressure with volume

For a fixed mass of gas at constant temperature

$$pV = \text{constant} \quad (3)$$

Combining the laws

The three equations can be combined, giving

$$\frac{pV}{T} = \text{constant}$$

For cases in which p, V and T all change from, say, p_1, V_1 and T_1 to p_2, V_2 and T_2, then

$$\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2} \quad (4)$$

Worked example

A bicycle pump contains 50 cm^3 of air at 17°C and at 1.0 atmosphere pressure (atm). Find the pressure when the air is compressed to 10 cm^3 and its temperature rises to 27°C.

We have

$p_1 = 1.0\,\text{atm}$

$p_2 = ?$

$V_1 = 50\,\text{cm}^3$

$V_2 = 10\,\text{cm}^3$

$T_1 = 273 + 17 = 290\,\text{K}$

$T_2 = 273 + 27 = 300\,\text{K}$

From equation (4) we get

$$p_2 = p_1 \times \frac{V_1}{V_2} \times \frac{T_2}{T_1} = 1 \times \frac{50}{10} \times \frac{300}{290} = 5.2\,\text{atm}$$

Note that: (i) all temperatures must be in K; (ii) any units can be used for p and V provided the same units are used on both sides of the equation; (iii) in some calculations the volume of the gas has to be found at standard temperature and pressure, or 's.t.p.'. This is temperature 0°C and pressure 1 atmosphere (1 atm = 10^5 Pa).

Now put this into practice

1 A fixed mass of gas has a volume of 9 cm^3 at a pressure of 1×10^5 Pa at 27°C. Find its pressure when the volume is compressed to 5 cm^3 and its temperature rises to 37°C.

2 A certain quantity of gas has a volume of 40 cm^3 at a pressure of 2.0×10^5 Pa at 27°C. Find its temperature when the volume is 30 cm^3 and the pressure is 3.2×10^5 Pa.

Test yourself

5 In terms of particle motion describe the effect on the pressure of a fixed mass of gas when the temperature rises but the volume is kept constant.

6 Describe the effect on the pressure of a fixed mass of gas if the volume is reduced but the temperature of the gas is kept constant.

7 **a** Why is −273°C chosen as the starting temperature for the Kelvin scale of temperature?
  b How do the size of units on the Celsius and Kelvin scales of temperature compare?

Revision checklist

After studying Topic 2.1 you should know and understand:

- ✔ the different physical properties of solids, liquids and gases
- ✔ particle diagrams for the different states of matter
- ✔ the different particle structure of solids, liquids and gases
- ✔ how the particle model explains the physical properties of solids, liquids and gases.

After studying Topic 2.1 you should be able to:

- ✔ recall the terms describing changes in state of solids, liquids and gases
- ✔ explain temperature, absolute zero and change in pressure in terms of molecular motion
- ✔ describe the effect on the pressure of a fixed mass of gas caused by a change in temperature (at constant volume) and a change of volume (at constant temperature); describe the effect on the volume of a fixed mass of gas caused by a change in temperature (at constant pressure)
- ✔ convert temperatures between the Celsius and Kelvin scales of temperature using the equation T (in K) $= \theta$ (in °C) $+ 273$
- ✔ recall and use the equation $p_1V_1 = p_2V_2$ (for a fixed mass of gas at constant temperature).

Exam-style questions

1 Solids, liquids and gases are composed of particles. Which one of the following statements is *not* true?

A The particles in a solid vibrate about a fixed position.

B The particles in a liquid are arranged in a regular pattern.

C The particles in a gas exert negligibly small forces on each other, except during collisions.

D The densities of most liquids are about 1000 times greater than those of gases because liquid particles are much closer together than gas particles.

[Total: 1]

2 Sketch particle diagrams for

a a solid [2]

b a liquid [2]

c a gas. [2]

[Total: 6]

3 a Identify the state of matter in which the particles are furthest apart. [1]

b Explain, using the particle model of matter, how a gas exerts pressure on the surfaces of its container. [2]

c State and explain how the pressure changes when the temperature of the gas increases. [4]

[Total: 7]

4 a The following statements refer to the pressure exerted by a gas in a container. State whether each statement is *true* or *false*.

i Pressure is due to the particles of the gas bombarding the surfaces of the container. [1]

ii The pressure decreases if the gas is cooled at constant volume. [1]

iii The pressure increases if the volume of the container increases at constant temperature. [1]

b i Explain the significance of a temperature of −273°C in terms of particle motion. [2]

ii State the value of a temperature of −273°C on the Kelvin temperature scale. [1]

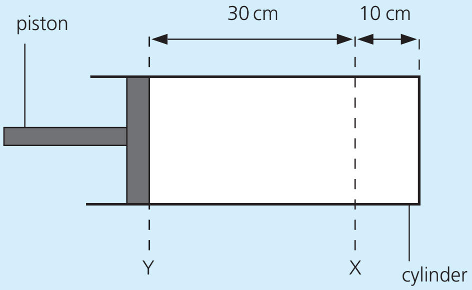
iii Calculate the value of a temperature of −200°C on the Kelvin scale of temperature. [1]

[Total: 7]

5 The piston in Figure 2.1.15 is pulled out of the cylinder from position X to position Y, without changing the temperature of the air enclosed. If the original pressure in the cylinder was 1.0×10^5 Pa, calculate

a the air pressure when the piston is at position Y [3]

b the air pressure when the piston is moved a further 10 cm to the left of position Y. [3]



▲ **Figure 2.1.15**

[Total: 6]

6 A certain quantity of gas has a volume of 30 cm^3 at a pressure of 1×10^5 Pa. Assuming the temperature remains constant, calculate the volume of the gas when the pressure is

a 2×10^5 Pa [3]

b 5×10^5 Pa. [3]

[Total: 6]

Alternative to Practical

7 The variation in pressure of a fixed mass of gas is measured for different volumes.
The results obtained are listed in the following table.

Pressure/10^5 Pa	Volume/cm^3	1/volume/cm^3
24	1.0	
12	2.0	
8	3.0	
6	4.0	
4	6.0	

a Plot a graph of pressure against volume. [3]
b Calculate values for 1/volume and enter them into the table. [1]
c Plot a graph of pressure against 1/volume. [3]
d Are the results in agreement with the equation $pV = \text{constant}$? [2]

[Total: 9]

2.2 Thermal properties and temperature

2.2.1 Thermal expansion of solids, liquids and gases

FOCUS POINTS

- ★ Describe thermal expansion in solids, liquids and gases and know some everyday applications of thermal expansion.
- ★ Use the motion and arrangement of particles in solids, liquids and gases to explain the relative order of magnitudes of their expansion as temperature increases.

As thermal energy is transferred to a material, the particles tend to move further apart. As you saw in Topic 2.1, the effect on heating a gas is large because the particles are free to move and expansion can easily occur. Expansion is much smaller in solids but thermal effects in a solid can still be important in conditions where there are wide temperature variations. Special features to absorb expansion need to be included in railway tracks and engineered structures such as bridges so that they do not distort on very hot days. In this topic you will encounter some everyday applications and consequences of expansion in solids and liquids.

When solids, liquids and gases are heated, the magnitude of the expansion for a given temperature rise is less for a liquid than a gas and even less for a solid where the particles are close together and the force of attraction between them is high.

Thermal expansion

According to the kinetic particle model (Topic 2.1.2) the particles of solids and liquids are in constant vibration. When heated they vibrate faster, so force each other a little further apart and **expansion** results.

Relative expansion of solids, liquids and gases

The linear (length) expansion of solids is small and for the effect to be noticed, the solid must be long and/or the temperature change must be large. For a 1 m length of steel the linear expansion is 0.012 mm for a 1°C rise in temperature.

The particles in a liquid are further apart, less ordered and are more mobile than in a solid so the interaction between the particles is less and expansion is easier for liquids than for solids. Liquids typically expand about five times more than solids for a given temperature rise. In gases, the interactions between particles are few because they are far apart and move about very quickly; this means they are able to expand much more easily than liquids. Typically, gases expand about 20 times more than liquids for a given temperature rise. These figures indicate that gases expand much more readily than liquids, and liquids expand more readily than solids.

Uses of expansion

Axles and gear wheels are major components of clocks on the small scale and wheeled vehicles from cars to trains on the large scale.

In Figure 2.2.1 the axle has been shrunk by cooling in liquid nitrogen at –196°C until the gear wheels can be slipped on to it. On regaining normal temperature, the axle expands to give a very tight fit.

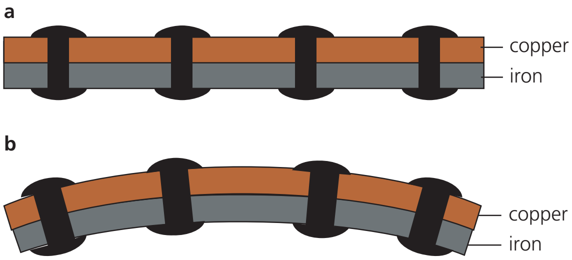
▲ **Figure 2.2.1** 'Shrink-fitting' of axles into gear wheels

In the kitchen, a tight metal lid can be removed from a glass jar by immersing the lid in hot water so that it expands and loosens. The expansion of a liquid or a gas can be used in thermometers to measure temperature (see p.104). An expanding gas drives the pistons in the engine of a motor car.

Bimetallic strip

If equal lengths of two different metals, such as copper and iron, are riveted together so that they cannot move separately, they form a **bimetallic strip** (Figure 2.2.2a). When heated, copper expands more than iron and to allow this the strip bends with copper on the outside (Figure 2.2.2b). If they had expanded equally, the strip would have stayed straight.

Bimetallic strips have many uses.

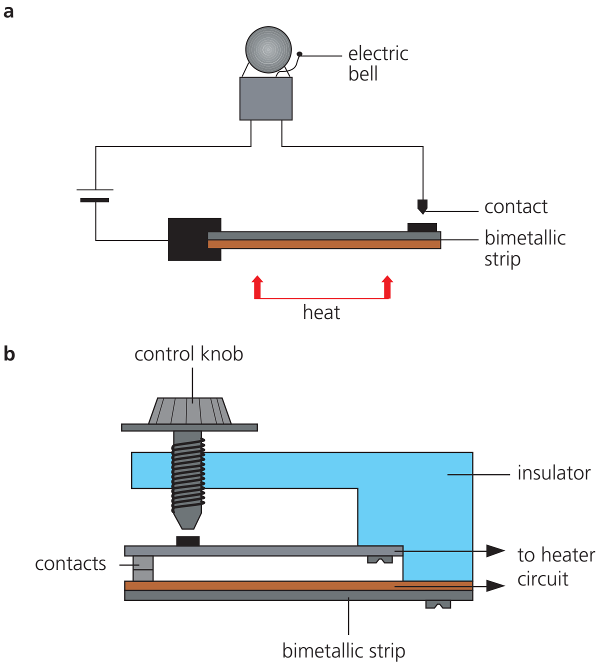


▲ **Figure 2.2.2** A bimetallic strip: **a** before heating; **b** after heating

Fire alarm

Heat from the fire makes the bimetallic strip bend and complete the electrical circuit, so ringing the alarm bell (Figure 2.2.3a).

A bimetallic strip is also used in this way to work the flashing direction indicator lamps in a car, being warmed by an electric heating coil wound round it.



▲ **Figure 2.2.3** Uses of a bimetallic strip: **a** fire alarm; **b** a thermostat in an iron

Thermostat

A **thermostat** keeps the temperature of a room or an appliance constant. The one in Figure 2.2.3b uses a bimetallic strip in the electrical heating circuit of, for example, an iron.

When the iron reaches the required temperature the strip bends down, breaks the circuit at the contacts and switches off the heater. After cooling a little, the strip remakes contact and turns the heater on again. A near-steady temperature results.

If the control knob is screwed down, the strip has to bend more to break the heating circuit and this requires a higher temperature.

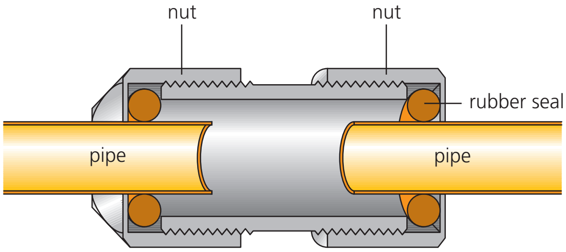
Precautions against expansion

In general, when matter is heated it expands and when cooled it contracts. If the changes are resisted large forces are created, which are sometimes useful but at other times are a nuisance.

Gaps used to be left between lengths of railway lines to allow for expansion in summer. They caused a familiar 'clickety-click' sound as the train passed over them. These days rails are welded into lengths of about 1 km and are held by concrete 'sleepers' that can withstand the large forces created without buckling. Also, at the joints the ends are tapered and overlap (Figure 2.2.4a). This gives a smoother journey and allows some expansion near the ends of each length of rail.

For similar reasons slight gaps are left between lengths of aluminium guttering. In central heating pipes 'expansion joints' are used to join lengths of pipe (Figure 2.2.4b); these allow the copper pipes to expand in length inside the joints when carrying very hot water.

▲ **Figure 2.2.4a** Tapered overlap of rails

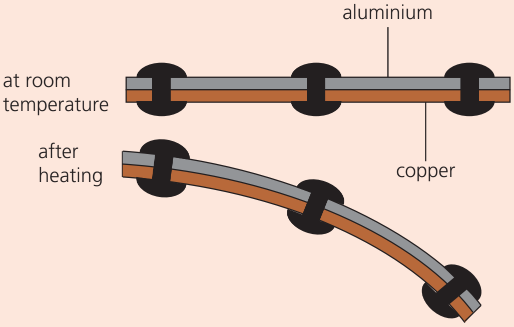


▲ **Figure 2.2.4b** Expansion joint

Test yourself

1 Explain why
  - **a** the metal lid on a glass jam jar can be unscrewed easily if the jar is inverted for a few seconds with the *lid* in very hot water
  - **b** furniture may creak at night after a warm day
  - **c** concrete roads are laid in sections with pitch (a compressible filling) between them.

2 A bimetallic strip is made from aluminium and copper. When heated it bends in the direction shown in Figure 2.2.5.
  - **a** Which metal expands more for the same rise in temperature, aluminium or copper?
  - **b** Sketch a diagram to show how the bimetallic strip would appear if it were cooled to below room temperature.

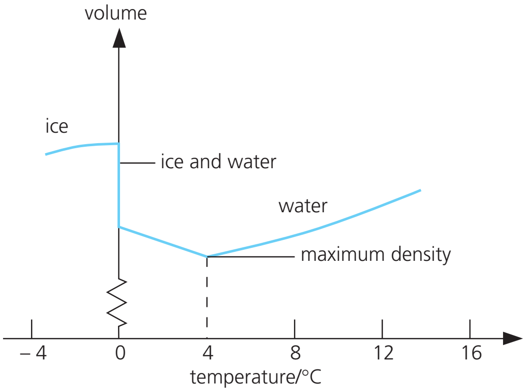


▲ **Figure 2.2.5**

Going further

Unusual expansion of water

As water is cooled to 4°C it contracts, as we would expect. However, between 4°C and 0°C it expands, surprisingly. Water has a *maximum density* at 4°C (Figure 2.2.6).

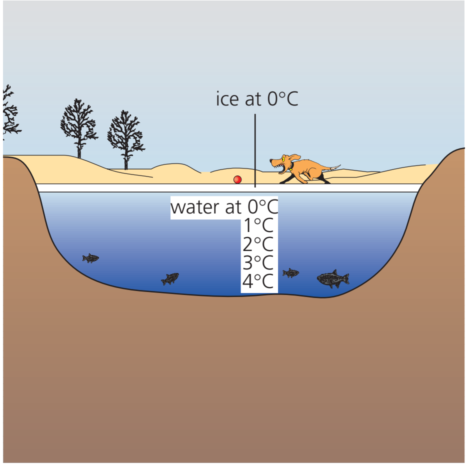


▲ **Figure 2.2.6** Water expands on cooling below 4°C.

At 0°C, when it freezes, a considerable volume expansion occurs and every 100 cm^3 of water becomes 109 cm^3 of ice. This accounts for the bursting of unlagged water pipes in very cold weather and for the fact that ice is less dense than cold water and so floats. Figure 2.2.7 shows a bottle of frozen milk, the main constituent of which is water.

▲ **Figure 2.2.7** Result of the expansion of water on freezing

The unusual (anomalous) expansion of water between 4°C and 0°C explains why fish survive in a frozen pond. The water at the top of the pond cools first, contracts and being denser sinks to the bottom. Warmer, less dense water rises to the surface to be cooled. When all the water is at 4°C the circulation stops. If the temperature of the surface water falls below 4°C, it becomes less dense and remains at the top, eventually forming a layer of ice at 0°C. Temperatures in the pond are then as in Figure 2.2.8.



▲ **Figure 2.2.8** Fish can survive in a frozen pond.

The volume expansion of water between 4°C and 0°C is due to the breaking up of the groups that water particles form above 4°C. The new arrangement requires a larger volume and more than cancels out the contraction due to the fall in temperature.

Liquid-in-glass thermometer

The temperature of a body tells us how hot the body is. It is measured using a thermometer, usually in degrees Celsius (0°C).

In the liquid-in-glass thermometer the liquid in a glass bulb expands up a capillary tube when the bulb is heated. The liquid must be easily seen and must expand (or contract) rapidly and by a large amount over a wide range of temperature. It must not stick to the inside of the tube or the reading will be too high when the temperature is falling.

Mercury and coloured alcohol are commonly used liquids in this type of thermometer. Mercury freezes at −39°C and boils at 357°C but is a toxic material. A non-toxic metal alloy substitute for mercury, such as Galinstan, is often used nowadays; it melts at −19°C and boils at 1300°C. Alcohol freezes at −115°C and boils at 78°C and is therefore more suitable for low temperatures.

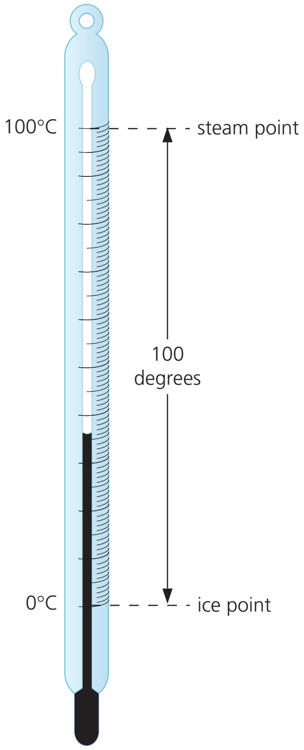
Going further

Scale of temperature

A scale and unit of temperature are obtained by choosing two temperatures, called the fixed points, and dividing the range between them into a number of equal divisions or degrees.

On the Celsius scale (named after the Swedish scientist Anders Celsius who suggested it), the lower fixed point is the temperature of pure melting ice and is taken as 0°C. The upper fixed point is the temperature of the steam above water boiling at normal atmospheric pressure, 10^5 Pa (or N/m^2), and is taken as 100°C.

When the fixed points have been marked on the thermometer, the distance between them is divided into 100 equal degrees (Figure 2.2.9). The thermometer now has a linear scale, in other words it has been calibrated or *graduated*.



▲ **Figure 2.2.9** A temperature scale in degrees Celsius

Test yourself

3 Explain the relative order of magnitude of the expansion of solids, liquids and gases.

4 a What is meant by the anomalous expansion of water?
  b Name two consequences of the unusual expansion of water.

5 Describe the action of a liquid-in-glass thermometer.

2.2.2 Specific heat capacity

FOCUS POINTS

★ **Know that an object's internal energy is increased when its temperature rises.**
★ **Explain a change in an object's temperature in terms of the change in kinetic energy of all its particles.**
★ **Define specific heat capacity, use the correct equation in calculations and describe experiments to measure it.**

Some materials require more heat than others to raise their temperature. As discussed in the previous topic, when the temperature of an object rises, its particles move more rapidly. The increase in the kinetic energy associated with this motion raises the internal energy of the object.

The extent of the increase in kinetic energy of the particles in a material when it is heated depends on the nature of the material and its state, and is measured in terms of specific heat capacity. The specific heat capacity of aluminium is higher than that of copper, so copper is a more energy efficient material to use for saucepans. In this topic you will find out how to measure and calculate the specific heat capacity of some solids and liquids.

The **internal energy** of an object is the energy associated with the motion of its particles.

When an object is heated and its temperature increases, there is an increase in the internal energy of the object. Both temperature and energy are scalar quantities.

Internal energy

The kinetic particle theory (Topic 2.1.2) regards temperature as a measure of the average kinetic energy (E_k) of the particles of the body. The greater this is, the faster the particles move and the higher the temperature of the body. Increasing the temperature of an object increases its internal energy because the kinetic energy of all the particles increases.

Thermal energy and temperature

It is important not to confuse the temperature of a body with the thermal energy that can be obtained from it. For example, a red-hot spark from a fire is at a higher temperature than the boiling water in a saucepan. In the boiling water the average kinetic energy of the particles is lower than in the spark; but since there are many more water particles, their total energy is greater, and therefore more thermal energy can be supplied by the water than by the spark.

> Thermal energy is transferred from a body at a higher temperature to one at a lower temperature.

This is because the average kinetic energy (and speed) of the particles in the hot body falls as a result of the collisions with particles of the cold body whose average kinetic energy, and therefore temperature, increases. When the average kinetic energy of the particles is the same in both bodies, they are at the same temperature. For example, if the red-hot spark landed in the boiling water, thermal energy would be transferred from it to the water even though much more thermal energy could be obtained from the water.

Specific heat capacity

If 1 kg of water and 1 kg of paraffin are heated in turn for the same time by the same heater, the temperature rise of the paraffin is about *twice* that of the water. Since the heater transfers equal amounts of thermal energy to each liquid, it seems that different substances require different amounts of energy to cause the same temperature rise in the same mass, say 1°C in 1 kg.

The amount of energy required to raise the temperature of a particular substance by one degree is measured by its **specific heat capacity** (symbol c).

The specific heat capacity of a substance is defined as the energy required per unit mass per unit temperature increase.

In physics, the word 'specific' means that unit mass is being considered.

In general, for a mass m, receiving energy ΔE which results in a change in temperature $\Delta\theta$, this can be written in equation form as:

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

where c is the specific heat capacity of a material of mass m whose temperature changes by $\Delta\theta$ when its internal energy increases by ΔE. In words this is written as:

$$\text{specific heat capacity} = \frac{\text{change in energy}}{\text{mass} \times \text{change in temperature}}$$

Internal energy is measured in joules (J) and the unit of specific heat capacity is the joule per kilogram per °C, i.e. J/(kg °C).

The equation for specific heat can be rearranged to give the equation:

$$\Delta E = mc\Delta\theta = \text{mass} \times \text{specific heat capacity} \times \text{change in temperature}$$

Key definition

Specific heat capacity the energy required per unit mass per unit temperature increase

Worked example

If 20 000 J is supplied to a mass of 5 kg and its temperature rises from 15°C to 25°C, calculate the specific heat capacity of the mass.

Using $c = \dfrac{\Delta E}{m\Delta\theta}$

$$c = \frac{20000\ \text{J}}{(5\,\text{kg} \times (25-15)\,^\circ\text{C})} = \frac{20000\ \text{J}}{50\ \text{kg}\,^\circ\text{C}}$$

$$= \frac{400\,\text{J}}{\text{kg}\,^\circ\text{C}}$$

Now put this into practice

1 If 25 000 J of energy is supplied to a mass of 2 kg and its temperature rises from 10°C to 35°C, calculate the specific heat capacity of the mass.

2 How much energy must be supplied to a mass of 3 kg of material of specific heat capacity = 500 J/(kg °C) to raise its temperature by 10°C?

Practical work

Finding specific heat capacities

Safety

- Eye protection must be worn.
- Take care as the pan and water and aluminium block may become hot.

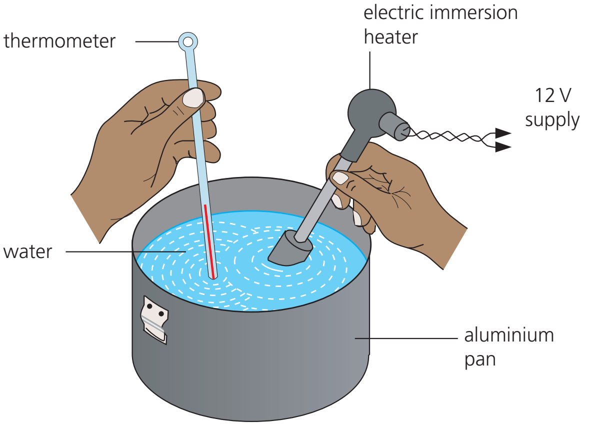
You need to know the power of the 12 V electric immersion heater to be used.

Precaution: Do not use one with a cracked seal.

A 40 W heater transfers 40 joules of energy from an electric current to thermal energy per second. If the power is not marked on the heater, ask about it.

Water

Weigh out 1 kg of water into a container, such as an aluminium saucepan. Note the temperature of the water, insert the heater (Figure 2.2.10), switch on the 12 V supply and start timing. Stir the water and after 5 minutes switch off but continue stirring and note the *highest* temperature reached.



▲ **Figure 2.2.10**

Assuming that the energy supplied by the heater equals the energy received by the water, work out the specific heat capacity of water in J/(kg °C), as shown below:

$$\text{energy transferred to water (J)} = \text{power of heater (J/s)} \times \text{time heater on (s)}$$

then the

$$\text{specific heat capacity of water} = \frac{\text{change in energy of the water (J)}}{\text{mass (kg)} \times \text{temp. rise (°C)}}$$

1 Suggest sources of error in the experiment described on the previous page to find the specific heat capacity of water.

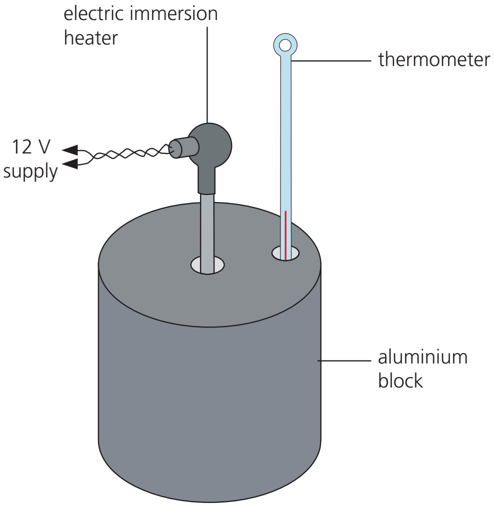
2 In an experiment to determine the specific heat capacity of water, the temperature rise of 1 kg of water is found to be 2.5°C when the water is heated by a 40 W heater for 5 minutes. Calculate the specific heat capacity of water.

Aluminium

An aluminium cylinder weighing 1 kg and having two holes drilled in it is used. Place the immersion heater in the central hole and a thermometer in the other hole (Figure 2.2.11).

Note the temperature, connect the heater to a 12 V supply and switch it on for 5 minutes. When the temperature stops rising, record its highest value.

Calculate the specific heat capacity as before.



▲ **Figure 2.2.11**

3 Suggest a source of error in the experiment to measure the specific heat capacity of aluminium and suggest how the experiment could be improved.

4 In an experiment to determine the specific heat capacity of aluminium, the temperature rise of an aluminium cylinder weighing 1 kg is found to be 12.5°C when the cylinder is heated by a 40 W heater for 5 minutes. Calculate the specific heat capacity of aluminium.

Importance of the high specific heat capacity of water

The specific heat capacity of water is 4200 J/(kg °C) and that of soil is about 800 J/(kg °C). As a result, the temperature of the sea rises and falls more slowly than that of the land. A certain mass of water needs five times more thermal energy than the same mass of soil for its temperature to rise by 1°C. Water also has to give out more energy to fall 1°C. Since islands are surrounded by water, they experience much smaller changes of temperature from summer to winter than large land masses such as Central Asia.

The high specific heat capacity of water (as well as its cheapness and availability) accounts for its use in cooling engines and in the radiators of central heating systems.

Worked example

a A tank holding 60 kg of water is heated by a 3 kW electric immersion heater. If the specific heat capacity of water is 4200 J/(kg °C), estimate the time for the temperature to rise from 10°C to 60°C.

Rearranging $c = \dfrac{\Delta E}{m\Delta\theta}$ gives $\Delta E = mc\Delta\theta$

Energy supplied to water = 3000 J/s × t, where t is the time of heating in seconds.

Assuming energy supplied = energy received by water

$$3000\,\text{J/s} \times t = \Delta E = mc\Delta\theta$$

$$\therefore t = \frac{(60 \times 4200 \times 50)\,\text{J}}{3000\ \text{J/s}} = 4200\ \text{s}\ (70\ \text{min})$$

b A piece of aluminium of mass 0.5 kg is heated to 100°C and then placed in 0.4 kg of water at 10°C. If the resulting temperature of the mixture is 30°C, what is the specific heat capacity of aluminium if that of water is 4200 J/(kg °C)?

When two substances at different temperatures are mixed, energy flows from the one at the higher temperature to the one at the lower temperature until both are at the same temperature – the temperature of the mixture. If there is no loss of energy, then in this case:

energy given out by aluminium = energy taken in by water

Using the equation $\Delta E = mc\Delta\theta$ and letting c be the specific heat capacity of aluminium in J/(kg °C), we have

$$\text{energy given out} = 0.5\,\text{kg} \times c \times (100 - 30)\,°\text{C}$$

$$\text{energy taken in} = 0.4\,\text{kg} \times 4200\,\text{J/(kg °C)} \times (30 - 10)\,°\text{C}$$

$$\therefore\ 0.5\,\text{kg} \times c \times 70\,°\text{C} = 0.4\,\text{kg} \times 4200\,\text{J/(kg °C)} \times 20\,°\text{C}$$

$$c = \frac{(4200 \times 8)\,\text{J}}{35\ \text{kg °C}} = 960\ \text{J/kg °C}$$

Now put this into practice

1 An electric kettle rated at 3 kW containing 1 kg of water is switched on. If the specific heat capacity of water is 4200 J/(kg °C), estimate the time for the water temperature to rise from 30°C to 100°C.

2 A metal sphere of mass 100 g is heated to 100°C and then placed in 200 g of water at 20°C. If the resulting temperature of the mixture is 25°C, what is the specific heat capacity of the metal if that of water is 4200 J/(kg °C)?

Test yourself

6 Which one of the following statements is *not* true?

- **A** Temperature tells us how hot an object is.
- **B** When the temperature of an object rises so does its internal energy.
- **C** Energy flows naturally from an object at a lower temperature to one at a higher temperature.
- **D** The particles of an object move faster when its temperature rises.

7 How much thermal energy is needed to raise the temperature by 10°C of 5 kg of a substance of specific heat capacity 300 J/(kg °C)?

8 How long will it take a 3 kW immersion heater to raise the temperature of 5 kg of water from 30°C to 50°C?

2.2.3 Melting, boiling and evaporation

FOCUS POINTS

- ★ Describe melting and boiling, including the temperatures for both for water.
- ★ Describe condensation, solidification and evaporation in terms of particles.
- ★ Understand the differences between boiling and evaporation.
- ★ Describe the factors that affect evaporation.
- ★ Describe latent heat in terms of particles.

To melt a bar of chocolate you will need to heat it. Melting and boiling require the input of energy to change the state of matter from solid to liquid or from liquid to gas. In the reverse changes, energy is released. During a change of state there is no change in temperature until the process is complete. The kinetic particle model can help us to understand the processes which occur during a change of state. In this section you will also learn how the model explains evaporation and cooling in terms of the escape of energetic particles from the surface of a liquid.

You will learn the differences between the processes of evaporation and boiling and the factors which affect the rate of cooling of an object.

When a solid is heated, it may melt and *change its state* from solid to liquid. If ice is heated it becomes water. The opposite process, freezing, occurs when a liquid solidifies.

A pure substance melts at a definite temperature, called the **melting temperature**; it solidifies at the same temperature – sometimes then called the **freezing temperature**. At standard atmospheric pressure, the melting temperature of water is 0°C.

Practical work

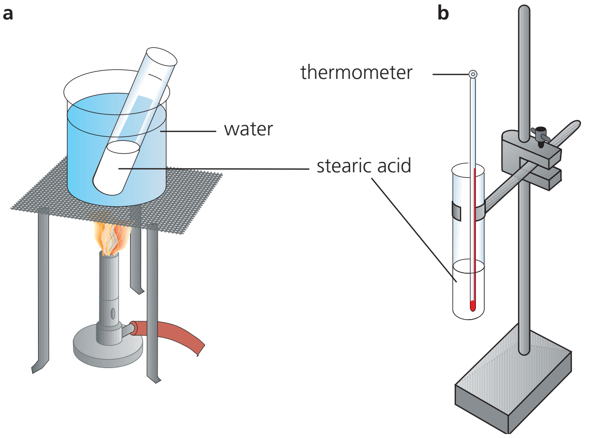
Cooling curve of stearic acid

Safety

- Eye protection must be worn.
- Take care when handling hot water and apparatus.

Half fill a test tube with stearic acid and place it in a beaker of water (Figure 2.2.12a). Heat the water until all the stearic acid has melted and its temperature reaches about 80°C.

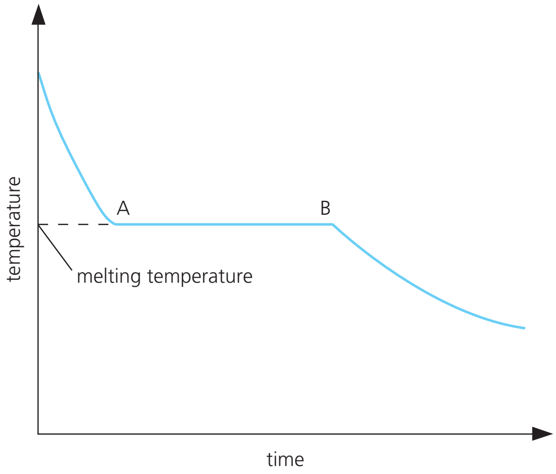
Remove the test tube and arrange it as in Figure 2.2.12b, with a thermometer in the liquid stearic acid. Record the temperature every minute until it has fallen to 60°C.



▲ **Figure 2.2.12**

5 Plot a graph of temperature against time (a cooling curve) and identify the freezing temperature of stearic acid.

6 The cooling curve (a plot of temperature against time) for a pure substance is shown in Figure 2.2.13. Why is the cooling curve flat in the region AB?



▲ **Figure 2.2.13** Cooling curve

7 What is happening to the liquid over region AB in Figure 2.2.13?

8 Is the rate of cooling faster or slower at higher temperatures in Figure 2.2.13?

Solidifying, melting and boiling

The previous experiment shows that the temperature of liquid stearic acid falls until it starts to solidify (at 69°C) and remains constant until it has all solidified. The cooling curve in Figure 2.2.13 is for a pure substance; the flat part AB occurs at the melting temperature when the substance is solidifying.

During *solidification* a substance transfers thermal energy to its surroundings but its temperature does not fall. Conversely when a solid is *melting*, the energy supplied does not cause a temperature rise; energy is transferred but the substance does not get hotter. For example, the temperature of a well-stirred ice–water mixture remains at 0°C until all the ice is melted. Similarly, when energy is supplied to a boiling liquid, the temperature of the liquid does not change. The temperature of pure water boiling at standard atmospheric pressure is 100°C.

Latent heat of fusion

Energy that is transferred to a solid during melting or given out by a liquid during solidification is called **latent heat of fusion**. Latent means hidden and fusion means melting. Latent heat does not cause a temperature change; it seems to disappear.

Going further

Specific latent heat of fusion

The specific latent heat of fusion (l_f) of a substance is the quantity of heat needed to change *unit mass* from solid to liquid without temperature change.

Specific latent heat is measured in J/kg or J/g. In general, the quantity of heat ΔE needed to change a mass m from solid to liquid is given by

$$\Delta E = m \times l_f$$

Practical work

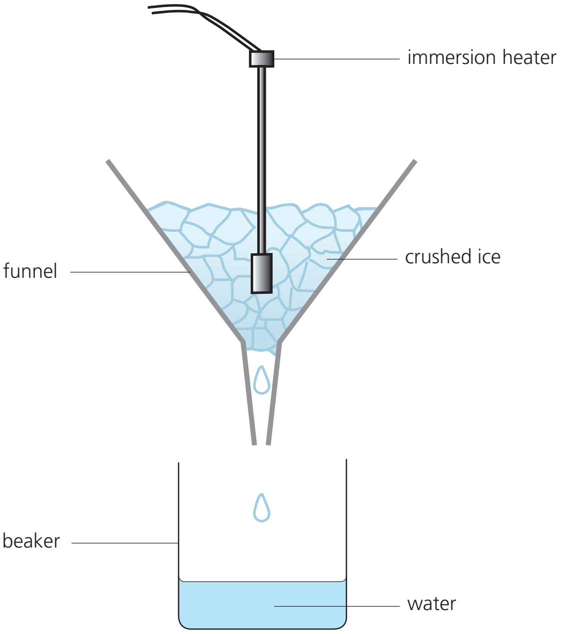
Specific latent heat of fusion for ice

Safety

- Eye protection must be worn.

Through measurement of the mass of water m produced when energy ΔE is transferred to melting ice, the specific latent heat of fusion for ice can be calculated.

Insert a 12 V electric immersion heater of known power P into a funnel, and pack crushed ice around it as shown in Figure 2.2.14.



▲ **Figure 2.2.14**

To correct for heat transferred from the surroundings, collect the melted ice in a beaker for time t (e.g. 4 minutes); weigh the beaker plus the melted ice, m_1. Empty the beaker, switch on the heater, and collect the melted ice for the same time t; re-weigh the beaker plus the melted ice, m_2. The mass of ice melted by the heater is then

$$m = m_2 - m_1$$

The energy supplied by the heater is given by $\Delta E = P \times t$, where P is in J/s and t is in seconds; ΔE will be in joules. Alternatively, a joulemeter can be used to record ΔE directly.

9 Use your data to calculate the specific latent heat of fusion, l_f, for ice from the equation $\Delta E = m \times l_f$

10 What correction is made in this experiment to measure the specific latent heat of fusion of ice to compensate for heat gained from the surroundings?

11 How could you reduce heat loss to the surroundings in this experiment?

Latent heat of vaporisation

Latent heat is also needed to change a liquid into a vapour. The reading of a thermometer placed in water that is boiling remains constant at 100°C even though energy, called **latent heat of vaporisation**, is still being transferred to the water from whatever is heating it. When steam condenses to form water, latent heat is given out. A scald from steam is often more serious than one from boiling water (Figure 2.2.15).

▲ **Figure 2.2.15** Steam from boiling water; invisible steam near the spout condenses into visible water droplets higher up.

Going further

Specific latent heat of vaporisation

The specific latent heat of vaporisation (l_v) of a substance is the quantity of heat needed to change unit mass from liquid to vapour without change of temperature.

Again, the specific latent heat is measured in J/kg or J/g. In general, the quantity of heat ΔE to change a mass m from liquid to vapour is given by

$$\Delta E = m \times l_v$$

To change 1 kg of water at 100°C to steam at 100°C needs over *five* times as much heat as is needed to raise the temperature of 1 kg of water at 0°C to water at 100°C.

Test yourself

9 1530°C 100°C 55°C 37°C 19°C 0°C −12°C −50°C

From the above list of temperatures choose the most likely value for *each* of the following:

- **a** the melting temperature of iron
- **b** the temperature of a room that is comfortably warm
- **c** the melting temperature of pure ice at normal pressure
- **d** the boiling temperature of water
- **e** the normal body temperature of a healthy person.

10 a Why is ice good for cooling drinks?

b Why do engineers often use superheated steam (steam above 100°C) to transfer heat?

Change of state and the kinetic particle model

Melting and solidification

The kinetic particle model explains the energy absorbed in melting as being the energy that enables the particles of a solid to overcome the intermolecular forces that hold them in place, and when it exceeds a certain value, they break free. Their vibratory motion about fixed positions changes to the slightly greater range of movement they have as liquid particles, and the solid melts. In the reverse process of solidification in which the liquid returns to the solid state, where the range of movement of the particles is less, potential energy is transferred from the particles to thermal energy in the surroundings.

The energy input in melting is used to increase the potential energy of the particles, but not their average kinetic energy (E_k) as happens when the energy input causes a temperature rise.

Vaporisation and condensation

If liquid particles are to overcome the forces holding them together and gain the freedom to move around independently as gas particles, they need a large amount of energy. This energy increases the potential energy of the particles but not their kinetic energy. Energy is also required to push back the surrounding atmosphere in the large expansion that occurs when a liquid vaporises. In the reverse process of condensation, in which a vapour returns to the liquid state, where the particles are closer together, potential energy is transferred from the particles to thermal energy in the surroundings.

Boiling and evaporation

At standard atmospheric pressure, the boiling temperature of water is 100°C.

Boiling

For a pure liquid, boiling occurs at a definite temperature called its *boiling temperature* and is accompanied by bubbles that form within the liquid, containing the gaseous or vapour form of the particular substance.

Energy is needed in both evaporation and boiling and is stored in the vapour, from which it is released when the vapour is cooled or compressed and changes to liquid again.

Evaporation

A few energetic particles close to the surface of a liquid may escape and become gas particles. This process of **evaporation** occurs at all temperatures.

Conditions affecting evaporation

Evaporation happens more rapidly when

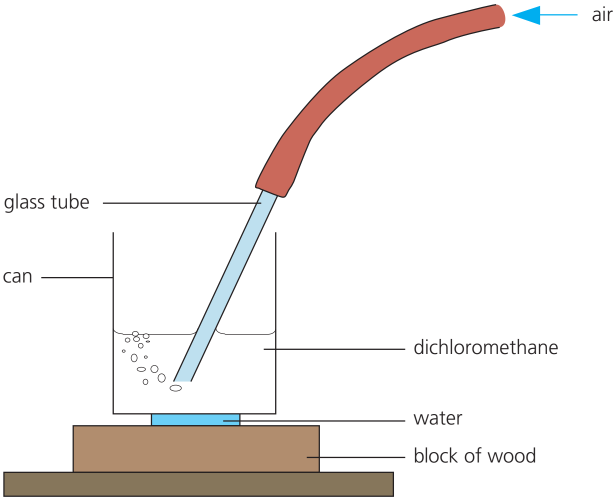
- the *temperature is higher*, since then more particles in the liquid are moving fast enough to escape from the surface
- the *surface area of the liquid is large*, so giving more particles a chance to escape because more are near the surface
- a *wind* or *draught* is blowing over the surface carrying vapour particles away from the surface, thus stopping them from returning to the liquid and making it easier for more liquid particles to break free. (Evaporation into a vacuum occurs much more rapidly than into a region where there are gas particles.)

Cooling by evaporation

In evaporation, energy is transferred to the liquid from its surroundings, as may be shown by the following demonstration, *done in a fume cupboard*.

Demonstration

Dichloromethane is a volatile liquid, i.e. it has a low boiling temperature and evaporates readily at room temperature, especially when air is blown through it (Figure 2.2.16). Energy is transferred first from the liquid itself and then from the water below the can. The water soon freezes causing the block and can to stick together.



▲ **Figure 2.2.16** Demonstrating cooling by evaporation

Explanation

Evaporation occurs when faster-moving particles escape from the surface of the liquid. The average speed and therefore the average kinetic energy of the particles left behind decreases, i.e. the temperature of the liquid falls.

Cooling by contact

When evaporation occurs from a liquid and the average kinetic energy of the remaining particles decreases, the liquid cools. In Topic 2.3.1 we will see that thermal energy flows from a hotter to a colder object by conduction. If an object is in contact with the liquid during evaporation, thermal energy will flow from the object to the liquid. The object will cool until its temperature equals that of the liquid.

Uses

Water evaporates from the skin when we sweat. This is the body's way of losing unwanted heat and keeping a constant temperature. After vigorous exercise there is a risk of the body being overcooled, especially in a draught; it is then less able to resist infection.

Ether acts as a local anaesthetic by chilling (as well as cleaning) your arm when you are having an injection. Refrigerators, freezers and air-conditioning systems use cooling by evaporation on a large scale.

Volatile liquids are used in perfumes.

Test yourself

11 a When a solid is melting
  i does its temperature increase, decrease or remain constant
  ii is energy absorbed or released or neither
  iii does the kinetic energy of the particles increase, decrease or remain constant?
b When a liquid is boiling
  i does its temperature increase, decrease or remain constant
  ii does the potential energy of the particles increase, decrease or remain constant?

12 a Describe the process of evaporation in particle terms.
b How does the temperature of a liquid change during evaporation?

13 Some water is stored in a bag of porous material, such as canvas, which is hung where it is exposed to a draught of air. Explain why the temperature of the water is lower than that of the air.

Revision checklist

After studying Topic 2.2 you should know and understand:

✔ that a rise in the temperature of an object increases its internal energy
✔ the relation between an object's temperature and the kinetic energy of the particles
✔ that melting and boiling occur without a change in temperature and recall those temperatures for water.

After studying Topic 2.2 you should be able to:

✔ describe the thermal expansion of solids and liquids
✔ describe precautions taken against expansion and uses of expansion
✔ explain the relative order of magnitude of the expansion of solids, liquids and gases
✔ distinguish between evaporation and boiling
✔ define specific heat capacity, c, and solve problems using the equation

$$\text{specific heat capacity} = \frac{\text{change in energy}}{\text{mass} \times \text{change in temperature}}$$

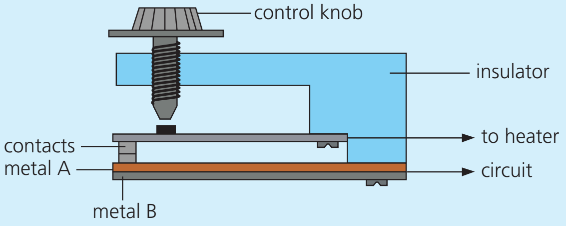
$$\left(c = \frac{\Delta E}{m\Delta\theta}\right)$$

✔ describe experiments to measure the specific heat capacity of metals and liquids by electrical heating
✔ describe condensation, solidification and evaporation processes in terms of the kinetic particle model
✔ explain latent heat using the kinetic particle model
✔ explain cooling by evaporation
✔ recall the factors which affect evaporation.

Exam-style questions

1 a A gas expands more easily than a liquid. Explain in terms of the motion and arrangement of particles. [3]
b Explain why the ends of railway lines are tapered and overlapped at joints. [2]
[Total: 5]

2 A bimetallic thermostat for use in an iron is shown in Figure 2.2.17.



▲ **Figure 2.2.17**

State if the following statements are *correct* or *incorrect*.
A It operates by the bimetallic strip bending away from the contact. [1]
B Metal A expands more per degree of temperature rise than metal B. [1]
C Screwing in the control knob raises the temperature at which the contacts open. [1]
[Total: 3]

3 The same quantity of thermal energy was given to different masses of three substances A, B and C. The temperature rise in each case is shown in the table. Calculate the specific heat capacities of A, B and C.

Material	Mass/kg	Thermal energy given/J	Temp. rise/°C
A	1.0	2000	1.0
B	2.0	2000	5.0
C	0.5	2000	4.0

[3 marks for each of A, B, C]

[Total: 9]

4 **a** The fruit in a hot fruit pie always seems hotter than the pastry. Why? [2]

b Calculate the temperature rise of 3 kg of a material of specific heat capacity 500 J/(kg °C) when it is heated with 15 000 J of energy. [3]

[Total: 5]

5 **a** A certain liquid has a specific heat capacity of 4.0 J/(g °C). How much energy must be supplied to raise the temperature of 10 g of the liquid from 20°C to 50°C? [3]

b Explain why a bottle of milk keeps better when it stands in water in a porous pot in a draught. [3]

[Total: 6]

6 **a** Define

i melting temperature
ii boiling temperature
iii freezing temperature. [3]

b State

i the melting temperature of ice
ii the boiling temperature of water

at standard atmospheric pressure. [2]

c State if energy is absorbed or released when

i a liquid solidifies
ii a gas condenses. [2]

[Total: 7]

7 A drink is cooled more by ice at 0°C than by the same mass of water at 0°C.
This is because ice

A floats on the drink [1]
B has a smaller specific heat capacity [1]
C gives out energy to the drink as it melts [1]
D absorbs energy from the drink to melt [1]
E is a solid. [1]

State whether each of the above statements is *correct* or *incorrect*.

[Total: 5]

Alternative to Practical

8 In an experiment to investigate the cooling of a liquid to a solid, a test tube containing a pure solid is warmed in a beaker of hot water until it has completely melted to a liquid and has reached a temperature of 90°C. The tube is then removed from the hot water and the temperature recorded every 2 minutes while the liquid cools to a solid. The results are given in the following table.

Time/minutes	0	2	4	6	8	10	12	14	16	18
Temperature/°C	90	86	82	81	80	80	79	76	73	72

a Plot a graph of temperature versus time. [4]

b Determine the melting temperature of the solid and explain your choice. [2]

c Explain what happens to the arrangement of the particles in the liquid during solidification. [2]

[Total: 8]

9 A student is investigating the factors that affect the rate of evaporation from a liquid surface.
The following apparatus is available:

- electronic balance (precision 0.1 g)
- shallow containers with different base areas
- stopwatch
- hairdryer
- hot water.

Plan an experiment to investigate the effect on the rate of evaporation of a liquid of **i** surface area and **ii** draughts.
You should:

- explain briefly how you would carry out the experiment
- state the key variables you would control
- draw a table (or tables) with column headings
- state how you would draw a conclusion from your results.

[Total: 6]

2.3 Transfer of thermal energy

2.3.1 Conduction

FOCUS POINTS

- ★ Know how to investigate whether a material is a good or poor thermal conductor.
- ★ Use atomic or molecular lattice vibrations and the movement of free (delocalised) electrons in metallic conductors to describe thermal conduction in solids.
- ★ Understand that good thermal conductors conduct thermal energy better than thermal insulators and some solids are better thermal conductors than others.

Heat from a stove is quickly transferred to all parts of a metal saucepan; metals are good conductors of heat. A poor thermal conductor, such as plastic, is often used for the handle of a saucepan to keep it cool. In this topic you will encounter experiments that demonstrate the properties of both good and bad thermal conductors.

Thermal energy can be transferred in various ways. In a solid an increase in temperature produces stronger local vibrations of the particles that are transferred to their neighbours and thermal energy is transferred progressively through the material. This is a slow process but is the main way of transferring energy in poor conductors. In good conductors, the main way of transferring thermal energy is by free electrons in the conductor; these can transfer energy from particle to particle very quickly.

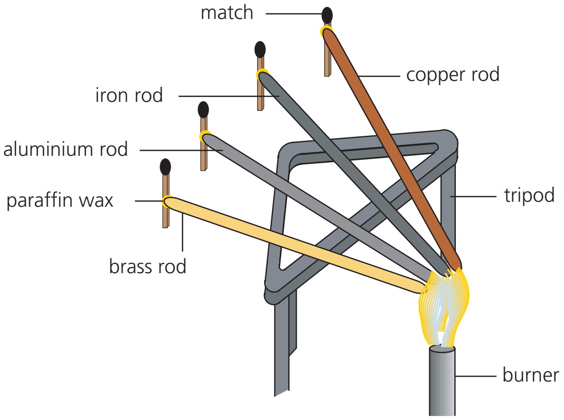
A knowledge of how thermal energy travels is needed to keep a building or a house at a comfortable temperature in winter and in summer, if it is to be done economically and efficiently.

Conduction

The handle of a metal spoon held in a hot drink soon gets warm. Thermal energy passes along the spoon by **conduction**.

Conduction is the flow of thermal energy (heat) through matter from places of higher temperature to places of lower temperature without movement of the matter as a whole.

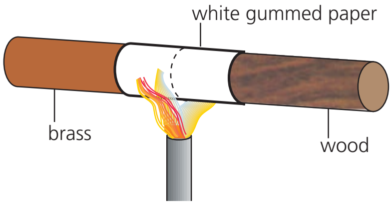
A simple demonstration of the different conducting powers of various metals is shown in Figure 2.3.1. A match is fixed to one end of each rod using a little melted wax. The other ends of the rods are heated by a burner. When the temperatures of the far ends reach the melting temperature of wax, the matches drop off. The match on copper falls first, showing it is the best **conductor**, followed by aluminium, brass and then iron.



▲ **Figure 2.3.1** Comparing conducting powers

Thermal energy is conducted faster through a rod if it has a large cross-sectional area, is short and has a large temperature difference between its ends.

Most metals are good thermal conductors; materials such as wood, glass, cork, plastics and fabrics are thermal **insulators** (poor conductors). The arrangement in Figure 2.3.2 can be used to show the difference between brass and wood. If the rod is passed through a flame several times, the paper over the wood scorches but not the paper over the brass. The brass conducts the thermal energy away from the paper quickly, preventing the paper from reaching the temperature at which it burns. The wood conducts the thermal energy away only very slowly.



▲ **Figure 2.3.2** The paper over the brass does not burn.

Metal objects below body temperature *feel* colder than objects made of poor conductors – even if all the objects are at exactly the same temperature – because the metal objects carry thermal energy away faster from the hand.

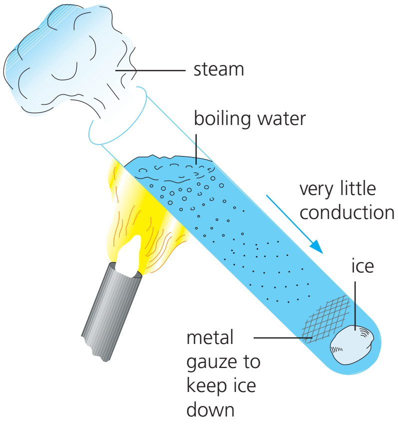
Going further

Conduction in liquids and gases

Liquids and gases also conduct thermal energy but only very slowly. Water is a very poor thermal conductor, as shown in Figure 2.3.3. The water at the top of the tube can be boiled before the ice at the bottom melts.

Liquids and gases

Liquids and gases are generally less dense than solids and their particles are further apart. They do not have a regularly ordered particle structure, so it is difficult to set up lattice vibrations, and they do not usually have free electrons. They are therefore less good thermal conductors than solids.



▲ **Figure 2.3.3** Water is a poor conductor of thermal energy.

Conduction and the particle model

Two processes occur in metals. Metals have a large number of 'free' (delocalised) electrons (Topic 4.2.2) which move about within the metal. When one part of a metal is heated, the electrons there move faster (their kinetic energy increases) and move further. As a result, they are able to interact with particles in cooler parts, so passing on their energy and raising the temperature of these parts. This process occurs quickly.

The second process is much slower. The atoms or molecules at the hot part make colder neighbouring particles vibrate more vigorously. These atomic or molecular lattice vibrations are less important in metals, but are the only way conduction can occur in non-metals since these do not have free electrons; hence non-metals are poor conductors of heat and are good insulators.

There are many solids which have fewer free electrons available to transfer thermal energy than metals do and so are less good thermal conductors than metals but better thermal conductors than insulators. For example, the semiconductors used in electronic circuits can have a range of thermal conductivities between those of metals and insulators.

Test yourself

1 Explain what is meant by thermal conduction.

2.3.2 Convection

FOCUS POINTS

★ Know that thermal energy transfer in liquids and gases usually occurs by convection.
★ Use density changes to explain convection in liquids and gases.
★ Describe some experiments to show convection.

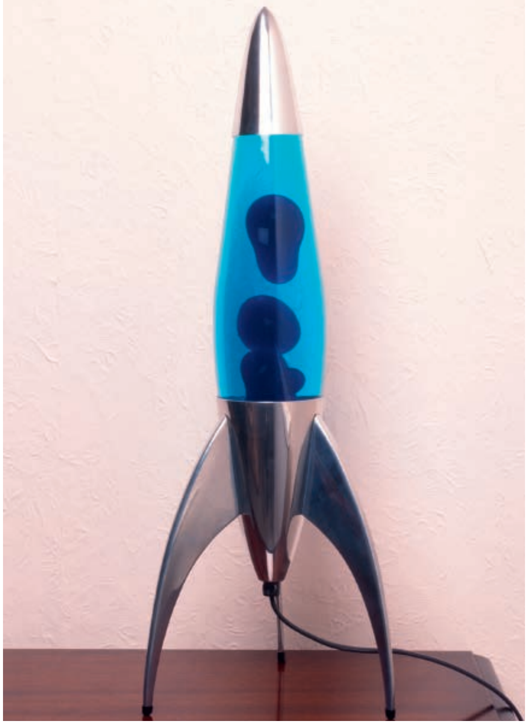
You may have a convector heater in your home which helps to keep you warm in winter. In convection, heat is transferred by the motion of matter and it is an important method for transferring thermal energy in liquids and gases. When the temperature of a fluid increases, thermal expansion reduces its density and the warmer, less dense parts of the fluid tend to rise, while cooler, denser parts will sink. The combination sets up fluid flows known as convection currents that transfer thermal energy from places of high temperature to those of lower temperature by motion of the fluid itself. In the case of a convector heater, convection currents are set up in the air in the room.

Convection in liquids

Convection is the usual method by which thermal energy (heat) travels through fluids such as liquids and gases. It can be shown in water by dropping a few crystals of potassium permanganate down a tube to the bottom of a beaker or flask of water. When the tube is removed and the beaker heated just below the crystals by a *small* flame (Figure 2.3.4a), purple streaks of water rise upwards and fan outwards.

▲ **Figure 2.3.4a** Convection currents shown by potassium permanganate in water.

Streams of warm, moving fluids are called **convection currents**. They arise when a fluid is heated because it expands, becomes less dense and is forced upwards by surrounding cooler, denser fluid which moves under it. We say 'hot water (or hot air) rises'. Warm fluid behaves like a cork released under water: being less dense it bobs up. Lava lamps (Figure 2.3.4b) use this principle.



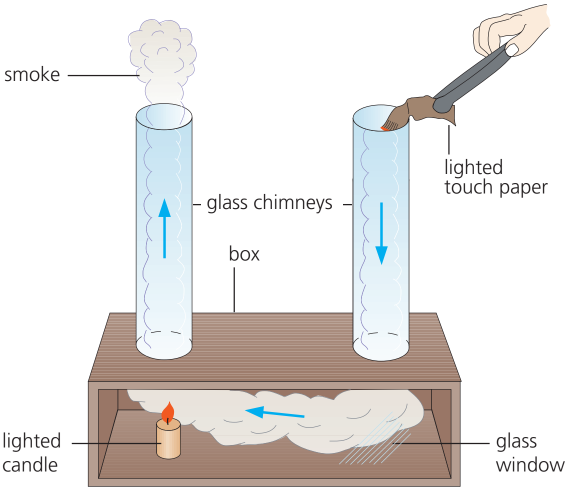
▲ **Figure 2.3.4b** Lava lamps make use of convection.

Convection is the flow of thermal energy through a fluid from places of higher temperature to places of lower temperature by movement of the fluid itself.

Convection in air

Black marks often appear on the wall or ceiling above a lamp or a radiator. They are caused by dust being carried upwards in air convection currents produced by the hot lamp or radiator.

A laboratory demonstration of convection currents in air can be given using the apparatus of Figure 2.3.5. The direction of the convection current created by the candle is made visible by the smoke from the touch paper (made by soaking brown paper in strong potassium nitrate solution and drying it).



▲ **Figure 2.3.5** Demonstrating convection in air

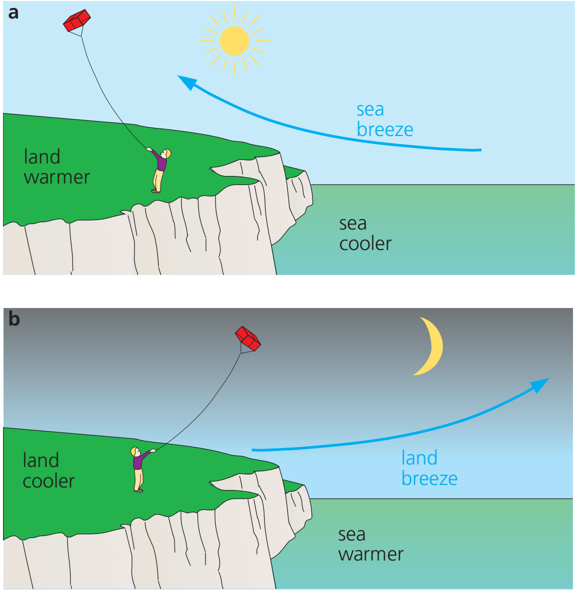
Going further

Natural convection currents

Coastal breezes

During the day the temperature of the land increases more quickly than that of the sea (because the specific heat capacity of the land is much smaller; see Topic 2.2.2). The hot air above the land rises and is replaced by colder air from the sea. A breeze from the sea results (Figure 2.3.6a).

At night the opposite happens. The sea has more thermal energy to transfer and cools more slowly. The air above the sea is warmer than that over the land and a breeze blows from the land (Figure 2.3.6b).



▲ **Figure 2.3.6** Coastal breezes are due to convection: **a** day; **b** night.

Gliding

Gliders, including hang-gliders (Figure 2.3.7), are carried along on hot air currents, called thermals.

▲ **Figure 2.3.7** Once airborne, a hang-glider pilot can stay aloft for several hours by flying from one thermal to another.

Test yourself

2 Explain the advantage of placing an electric immersion heater in a tank of water
  a near the top
  b near the bottom.
3 Why does hot air rise?

2.3.3 Radiation

FOCUS POINTS

- ★ Understand that thermal radiation is infrared radiation that does not require a transmission medium.
- ★ Describe the effects of surface colour and texture on the emission, absorption and reflection of infrared radiation.
- ★ Understand the factors which affect the amount of radiation emitted by an object.
- ★ Describe experiments to distinguish between good and bad absorbers and emitters of infrared radiation.
- ★ Know that surface temperature and surface area of an object affect the rate of emission of radiation.

On a sunny day it is pleasant to feel the warmth of the radiation reaching you from the Sun. Radiation is the third way of transferring thermal energy from one place to another. It does not need a transmission medium. On reaching Earth, the Sun's rays are partly reflected, absorbed or transmitted by objects. Shiny white surfaces are good reflectors of radiation but dull black surfaces are good absorbers. The efficiency of emission and absorption of radiation depends on the nature of the surface of the material.

The rate of radiation emission depends on the temperature and surface area of the object.

Radiation is a third way in which thermal energy can travel but, whereas conduction and convection both need matter to be present, radiation can occur in a vacuum; particles of matter are not involved. Radiation is the way thermal energy reaches us from the Sun.

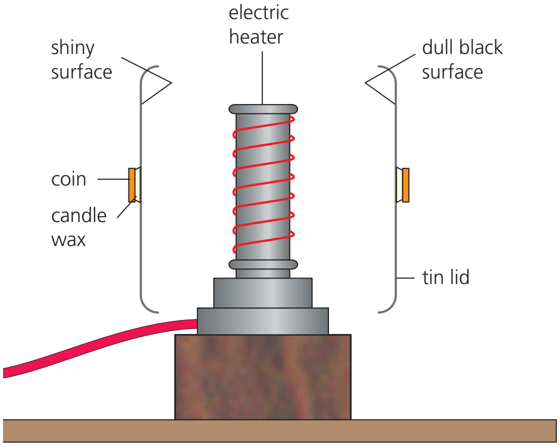
Radiation has all the properties of electromagnetic waves (Topic 3.3), and travels with the speed of light. Thermal radiation is **infrared radiation** and all objects emit this radiation. When it falls on an object, it is partly reflected, partly transmitted and partly absorbed: the absorbed radiation raises the temperature of the object.

Buildings in hot countries are often painted white (Figure 2.3.8). This is because white surfaces are good reflectors of radiation and so help to keep the houses cool.

▲ **Figure 2.3.8** White painted buildings

Good and bad absorbers

Some surfaces absorb radiation better than others, as may be shown using the apparatus in Figure 2.3.9. The inside surface of one lid is shiny and of the other dull black. The coins are stuck on the outside of each lid with candle wax. If the heater is midway between the lids, they each receive the same amount of radiation. After a few minutes the wax on the black lid melts and the coin falls off. The shiny lid stays cool and the wax unmelted.



▲ **Figure 2.3.9** Comparing absorbers of radiation

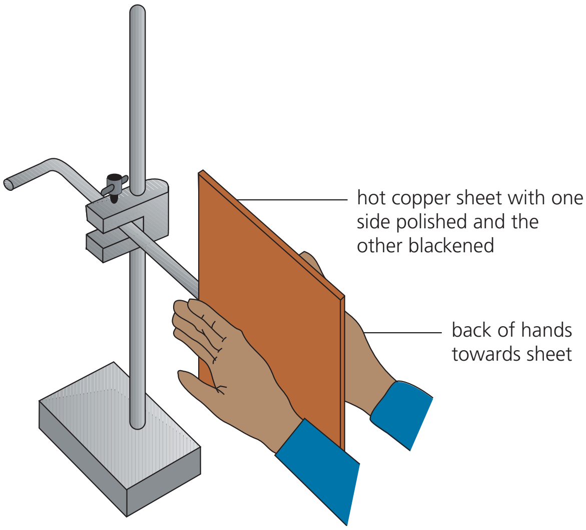
Dull black surfaces are *better* **absorbers** of radiation than *white shiny surfaces*, which are instead good **reflectors** of radiation. Reflectors on electric fires are made of polished metal because of its good reflecting properties.

Good and bad emitters

Some surfaces also emit radiation better than others when they are hot. If you hold the backs of your hands on either side of a hot copper sheet that has one side polished and the other side blackened (Figure 2.3.10), it will be found that your hands feel warmer near the dull black surface. The dull black surface is a *better* **emitter** *of radiation* than the shiny one.

The cooling fins on the heat exchangers at the back of a refrigerator are painted black so are good emitters of radiation and they lose heat more quickly. By contrast, saucepans that are polished are poor emitters and keep their heat longer.

In general, surfaces that are good absorbers of radiation are good emitters when hot.



▲ **Figure 2.3.10** Comparing emitters of radiation

Going further

Temperature and rate of emission of radiation

Radiation is emitted by all bodies above absolute zero and consists mostly of infrared radiation, but light and ultraviolet are also present if the body is very hot (e.g. the Sun). For an object to maintain a constant temperature, energy must transfer away from the object at the same rate that the object receives energy. If the average energy radiated is less than that absorbed, the temperature of the object will rise. If the average energy radiated is more than that absorbed, the temperature of the object will fall.

The greenhouse effect

The warmth from the Sun is not cut off by a sheet of glass but the warmth from a red-hot fire can be blocked by glass. The radiation from very hot bodies like the Sun is mostly light and short-wavelength infrared. The radiation from less hot objects, such as a fire, is largely long-wavelength infrared which, unlike light and short-wavelength infrared, cannot pass through glass.

Light and short-wavelength infrared from the Sun penetrate the glass of a greenhouse and are absorbed by the soil, plants, etc., raising their temperature. These in turn emit infrared but, because of their relatively low temperature, this has a long wavelength and is not transmitted by the glass. The greenhouse thus acts as a 'heat-trap' and its temperature rises.

Carbon dioxide and other gases such as methane in the Earth's atmosphere act in a similar way to the glass of a greenhouse in trapping heat radiated from the Earth's surface. This has serious implications for the global climate. For the average temperature of the Earth to remain constant, a balance must be achieved between the incoming radiation and the radiation emitted from the Earth's surface.

If there is a build-up of carbon dioxide and methane gases in the atmosphere, the balance between incoming radiation from the Sun and the average power emitted from the Earth will be upset.

Rate of cooling of an object

If the surface temperature of an object is higher than its surroundings, it emits radiation at a faster rate than it absorbs radiation from its surroundings. As a result, it cools until the two rates become equal and a constant temperature is reached. The higher the surface temperature of the object above its surroundings, and the larger its surface area, the greater the quantity of radiation it emits and the greater its rate of cooling.

Practical work

Rate of cooling

Safety

- Eye protection must be worn.
- Take care when handling hot water and its containers.

Place a thermometer in some hot water and wait until the temperature reaches a steady temperature above 80°C. Remove the thermometer from the water, and quickly wipe it dry with a paper towel. Record the temperature on the thermometer every 30 s as it cools away from draughts or any source of heat. Use your results to plot a graph of temperature against time.

1 In this experiment a student recorded the following temperatures on the thermometer as it cooled in air.

Time/s	0	30	60	90	120	150	180
Temperature/°C	80	63	51	42	36	31	28

a Plot a graph of temperature against time using the values given in the table.

b Calculate the temperature drop

  i between 0 and 90 s

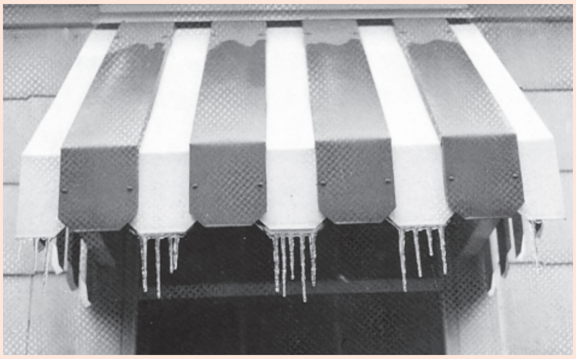
  ii between 90 s and 180 s.

c State the temperature range over which the thermometer cools most quickly.

d Does the thermometer emit radiation at a higher rate at the higher or lower temperatures?

Test yourself

4 The door canopy in Figure 2.3.11 shows clearly the difference between white and black surfaces when radiation falls on them. Explain why.



▲ **Figure 2.3.11**

5 What type of radiation is thermal radiation?

6 Why is frost less likely on a cloudy night than a clear one?

2.3.4 Consequences of thermal energy transfer

FOCUS POINTS

★ Explain everyday applications and consequences of thermal energy transfer by conduction, convection and radiation.

You have now learned about the three ways in which thermal energy can be transferred from one place to another: conduction, convection and radiation. Such transfers occur in many different situations in everyday living. Transfer of thermal energy by conduction from an external source enables us to heat cooking pots. Convection is often used in water and convector heaters in our homes. Radiation from the Sun can be felt directly and an infrared thermometer allows us to read temperature from a distance. In this topic you will learn more about the uses of both good conductors and poor conductors (insulators).

Uses of conductors

Good conductors

These are used whenever heat is required to travel quickly through something. Saucepans, boilers and radiators are made of metals such as aluminium, iron and copper which are all good conductors that transfer thermal energy quickly.

Thermal insulators (bad conductors)

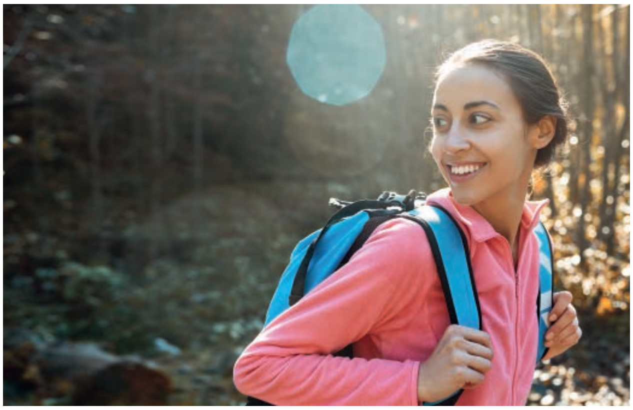
These are used when a slow transfer of thermal energy is required. A polystyrene cup will help to keep hot liquids warm or cold liquids cool (Figure 2.3.12d opposite). The handles of some saucepans are made of wood or plastic. Cork is used for table mats. These are insulating materials that transfer thermal energy only very slowly.

Air is one of the worst thermal conductors and so one of the best insulators. This is why houses with cavity walls (two layers of bricks separated by an air space) and double-glazed windows keep warmer in winter and cooler in summer.

Because air is such a bad conductor, materials that trap air, such as wool, felt, fur, feathers, polystyrene foam and fibreglass, are also very bad conductors. Some of these materials are used as thermal insulation to insulate water pipes, hot water cylinders, ovens, refrigerators and the walls and roofs of houses (Figures 2.3.12a and 2.3.12b). Others are used to make warm winter clothes like fleece jackets (Figure 2.3.12c opposite).

▲ **Figure 2.3.12a** Foam or wool in a cavity wall provides extra insulation.

▲ **Figure 2.3.12b** A thick layer of thermal insulation reduces energy loss through the roof of a building.



▲ **Figure 2.3.12c** Fleece jackets help to retain your body warmth.

▲ **Figure 2.3.12d** An insulated cup slows the transfer of thermal energy.

Wet suits are worn by divers and water skiers to keep them warm. The suit gets wet and a layer of water gathers between the person's body and the suit. The water is warmed by body heat and stays warm because the suit is made of an insulating fabric, such as neoprene (a synthetic rubber).

Practical work

Effect of insulation

Place the bulb of a thermometer in some melting ice until it reaches a temperature of 0°C. Remove the thermometer from the ice. Record the temperature on the thermometer every 5 s until it reaches room temperature. Repeat the experiment but wrap the bulb of the thermometer with insulation immediately you remove it from the ice. Use your results to plot graphs of temperature against time.

1 State the source of thermal energy when the temperature of the thermometer rises after it is removed from the ice.

2 How could the time taken for the thermometer to reach room temperature be increased?

Reducing energy losses from buildings

The inside of a building can only be kept at a steady temperature above that outside by heating it at a rate which equals the rate at which it is losing energy. The loss occurs mainly by conduction through the walls, roof, floors and windows. For a typical house where no special precautions have been taken, the contribution each of these makes to the total loss is shown in Table 2.3.1a.

As fuels (and electricity) become more expensive and the burning of fuels becomes of greater environmental concern (Topic 1.7.3), more people are considering it worthwhile to reduce energy losses from their homes. The substantial reduction of this loss which can be achieved, especially by wall and roof insulation, is shown in Table 2.3.1b.

▼ **Table 2.3.1** Energy losses from a typical house

a Percentage of total energy loss due to				
walls	**roof**	**floors**	**windows**	**draughts**
35	25	15	10	15
b Percentage of each loss saved by				
insulating walls	**insulating roof**	**carpets on floors**	**double glazing**	**draught excluders**
65	80	≈30	50	≈60
Percentage of total loss saved = 60				

Going further

Ventilation

In addition to supplying heat to compensate for the energy losses from a building, a heating system has also to warm the ventilated cold air, needed for comfort, which comes in to replace stale air.

If the rate of energy loss is, say, 6000 J/s, or 6 kW, and the warming of ventilated air requires 2 kW, then the total power needed to maintain a certain temperature (e.g. 20°C) in the building is 8 kW. Some of this is supplied by each person's 'body heat', estimated to be roughly equal to a 100 W heater.

Uses of convection

Convection currents set up by electric, gas and oil heaters help to warm our homes. Many so-called 'radiators' are really convector heaters. Warm air produced by the heater rises because it is less dense than the colder air above. The cold air sinks, is warmed by the heater and itself rises. A convection current is set up which helps to warm the whole room.

Convection currents also form in the water being heated in hot water tanks, kettles and kitchen pans, allowing water to be heated quickly.

Uses of radiation: infrared thermometer

An infrared thermometer detects the thermal radiation emitted by an object and converts it into an electrical signal. The temperature of the object can be determined from the radiant power detected and the value is shown on a digital display. It is a non-contact method and allows temperature to be measured at a distance. Infrared thermometers are frequently used to monitor the health of passengers arriving at an airport.

▲ **Figure 2.3.13** An infrared thermometer in use

Applications involving more than one type of thermal energy transfer

Car radiator

Both conduction and radiation occur in a car radiator which acts to dissipate the heat generated in the engine. It contains a fluid which circulates between the engine block and the radiator. Thermal energy is transferred to the fluid by conduction as it passes over the engine block. When the fluid enters the radiator, thermal energy is transferred by conduction to the radiator which then radiates energy in the infrared to the surroundings. The metal radiator is black and has a large surface so is a good emitter of radiation. In this way the fluid is cooled before it circulates back to the engine block.

Wood or coal fire

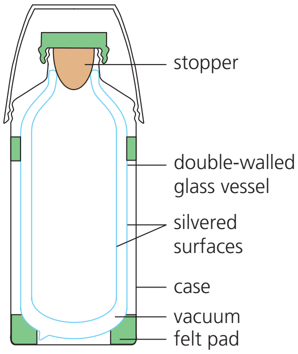
Radiation and convection occur when a room is heated by a wood- or coal-burning fire.

Thermal energy is radiated from the burning wood or coal and heats up objects in the room which absorb it. Air in contact with the hot wood or coal is warmed and rises upwards because it is less dense than the cold air above. Cooler air is drawn down to take its place and a convection current is set up which also transfers thermal energy into the room.

Vacuum flask

A vacuum or Thermos flask keeps hot liquids hot or cold liquids cold. It is very difficult for heat to travel into or out of the flask.

Transfer of thermal energy by conduction and convection is minimised by making the flask a double-walled glass vessel with a vacuum between the walls (Figure 2.3.14). Radiation is reduced by



▲ **Figure 2.3.14** The structure of a vacuum flask silvering both walls on the vacuum side. Then if, for example, a hot liquid is stored, the small amount of radiation from the hot inside wall is reflected back across the vacuum by the silvering on the outer wall. The slight energy loss that does occur is by conduction up the thin glass walls and through the stopper. If the flask is to be used to store a cold liquid, thermal energy from outside the flask is reflected from the inner wall.

Test yourself

7 Explain why on a cold day the metal handlebars of a bicycle feel colder than the rubber grips.

8 Identify the energy transfers which occur
  a when a radiator is used to cool the engine of a car
  b when a room is heated by a coal fire.

Revision checklist

After studying Topic 2.3 you should know and understand:

✔ that thermal energy transferred by infrared radiation does not require a medium
✔ the rate of radiation emission increases as the temperature or surface area of the object increases
✔ how thermal insulation is used to keep liquids cool and to reduce energy loss from buildings.

After studying Topic 2.3 you should be able to:

✔ describe experiments to show the different conducting powers of various substances and name good and bad conductors
✔ explain conduction using the kinetic particle model
✔ describe experiments to show convection in fluids (liquids and gases) and relate convection in fluids to density changes
✔ describe the effect of surface colour and texture on the emission, absorption and reflection of radiation and recall that good absorbers are also good emitters
✔ describe experiments to study factors affecting the absorption and emission of radiation
✔ explain some everyday applications of conduction, convection and radiation.

Exam-style questions

1 Describe an experiment to demonstrate the properties of good and bad thermal conductors. [Total: 4]

2 Explain in terms of particles how thermal energy is transferred by conduction in solids. [Total: 4]

3 **a** Explain how thermal energy is transferred by convection. [3]
  b Describe an experiment to illustrate convection in a liquid. [3]
  [Total: 6]

4 The following statements relate to the absorption and emission of radiation.
State which of the statements are *true* and which are *false*.
  A Energy from the Sun reaches the Earth by radiation only. [1]
  B A dull black surface is a good absorber of radiation. [1]
  C A shiny white surface is a good emitter of radiation. [1]
  D The best heat insulation is provided by a vacuum. [1]
  [Total: 4]

5 Describe the effect of surface colour and texture on the
  a emission of radiation [2]
  b reflection of radiation [2]
  c absorption of radiation. [2]
  [Total: 6]

6 **a** Describe an experiment to show the properties of good and bad emitters of infrared radiation. [4]

b Describe an experiment to show the properties of good and bad absorbers of infrared radiation. [4]

[Total: 8]

7 Explain why

a newspaper wrapping keeps hot things hot, e.g. fish and chips, and cold things cold, e.g. ice cream [1]

b fur coats would keep their wearers warmer if they were worn inside out [2]

c a string vest helps to keep a person warm even though it is a collection of holes bounded by string. [2]

[Total: 5]

8 Figure 2.3.15 illustrates three ways of reducing heat losses from a house.

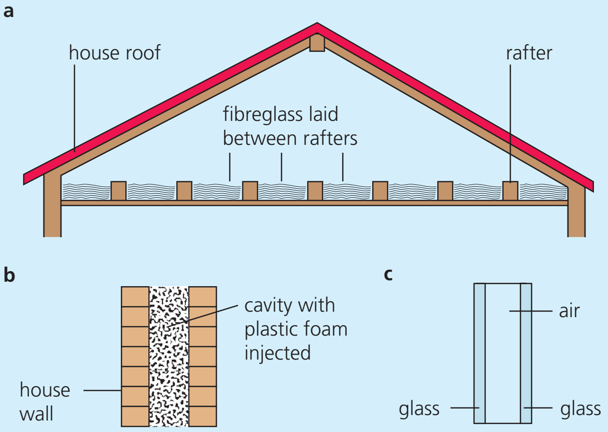
a Explain how each of the three methods reduces heat losses. [4]

b Why are fibreglass and plastic foam good substances to use? [2]

c Air is one of the worst conductors of heat. What is the advantage of replacing it by plastic foam as shown in Figure 2.3.15? [1]

d A vacuum is an even better heat insulator than air. Suggest one (scientific) reason why the double glazing should not have a vacuum between the sheets of glass. [1]

[Total: 8]



▲ **Figure 2.3.15 a** Roof insulation; **b** cavity wall insulation; **c** double glazing

Alternative to Practical

9 The manufacturers of roof insulation suggest that two layers of fibreglass are more effective than one. Describe how you might set up an experiment in the laboratory to test whether this is true.

The following apparatus is available:

- 250 cm^3 glass beaker
- measuring cylinder
- layers of fibreglass insulation
- thermometer
- stopwatch.

Other apparatus normally found in the school laboratory is also available.

You should

- explain briefly how you would carry out the investigation
- state the key variables that you would control
- give a table, or tables, with column headings to show how you would display your readings
- explain briefly how you would use your readings to reach a conclusion.

[Total: 6]