Block 2

Thermal physics

We are fortunate because we live on the Earth. The Earth is a planet orbiting the Sun at a distance of 150 million kilometres. The Sun keeps the Earth warm, with an average temperature of about 15 °C. At night, the temperature drops because we are facing away from the Sun, outwards into the coldness of space. Because the Earth spins, every part of the globe faces the Sun periodically and has a chance to warm up again after the cooling down of the night.

Things are different out in space. Space is cold and dark. Its average temperature is close to −270 °C. How can we know that? It is simple. Scientists have sent spacecraft like the one shown out into space to measure the temperature. The temperature probe used must be shielded from the Sun's rays and also from any warmth of the spacecraft itself. Measurements show that the average temperature of space is just 2.7 degrees above absolute zero, the coldest possible temperature.

In fact, the temperature of space had been correctly predicted before anyone had a chance to measure it. The prediction came from the Big Bang theory of the origin of the Universe. The idea is that, roughly 13.7 billion years ago, the Universe 'exploded' into existence. Ever since, it has been expanding and so cooling. When scientists measure the temperature of space, they are detecting the last remnants of the great fireball that was the early Universe.

In this block, we will look at some of these ideas in more detail. In particular, we will look at what we mean by temperature and how thermal (heat) energy travels around.

An artist's impression of the Cosmic Background Explorer. This spacecraft measured the temperature of space by detecting the radiation left over from the Big Bang. The gold-coloured 'skirt' shields the temperature sensors from heat from the Sun and Earth.

9

The kinetic model of matter

	Core	Describing solids, liquids and gases
	Core	Describing changes of state
	Core	Using the kinetic model to explain changes of state
E	**Extension**	Explaining the kinetic model in terms of the forces between particles
	Core	Explaining the behaviour of gases
E	**Extension**	Calculating changes in pressure and volume

Snow

Young people usually enjoy snow (Figure **9.1**). You may live in a country where snow is rarely seen. Alternatively, you may be snow-bound for several months of the year. If you do experience snow, you will know the excitement of the first fall of the winter. Everyone rushes out to have snowball fights, or to go tobogganing or skiing.

Snow is remarkable stuff. It is simply frozen water. Yet people such as the Inuit who live among snow have many different words for it, depending on how it is packed down, for instance. This can be vital information if you are interested in winter sports, since it determines the avalanche risk.

We are familiar with the changes that happen when snow or ice melts. A white or glassy solid changes into a transparent, colourless, runny liquid. Heat the liquid and it 'vanishes' into thin air. Although this sounds like a magic trick, it is so familiar that it does not strike us as surprising. The Earth is distinctive among the planets of the solar system in being the only planet on which water is found to exist naturally in all three of its physical states.

In this chapter, we will look at what happens when materials change their state – from solid to liquid to gas, and back again. By thinking about the particles, the atoms and molecules of which the material is made, we can build up a picture or model that describes changes of state and explains some of the things we observe when materials change from one state to another.

Figure 9.1 Dubai is a hot place, but you can still ski there on the artificial snow in this covered ski centre.

9.1 States of matter

We think of matter as existing in three states, **solid**, **liquid** and **gas**. What are the characteristic properties of each of these three states? We need to think about shape and size. Table 9.1 shows how these help us to distinguish between solids, liquids and gases. It may help you to think about ice, water and steam as examples of the three states of matter.

State	Size	Shape
solid	occupies a fixed volume	has a fixed shape
liquid	occupies a fixed volume	takes the shape of its container
gas	expands to fill its container	takes the shape of its container

Table 9.1 The distinguishing properties of the three states of matter.

Here is a trick to try on a small child. Pour a drink into a short, wide glass. Then pour it from that glass into a tall, narrow glass. Ask them which drink they would prefer. Many small children ask for the drink in the tall glass because it appears that there is more. Of course, you will realise that, although the drink changes its shape when you pour it from one container to another, its size (volume) stays the same.

Changes of state

Heat a solid and it melts to become a liquid. Heat the liquid and it boils to become a gas. Cool the gas and it becomes first a liquid and then a solid. These are **changes of state**. The names for these changes are shown in Figure 9.2. They are:

- **melting** – from solid to liquid
- **boiling** – from liquid to gas
- **condensing** – from gas to liquid
- **freezing** – from liquid to solid.

Another term for a liquid changing to a gas is **evaporation**. We will see the difference between evaporation and boiling shortly.

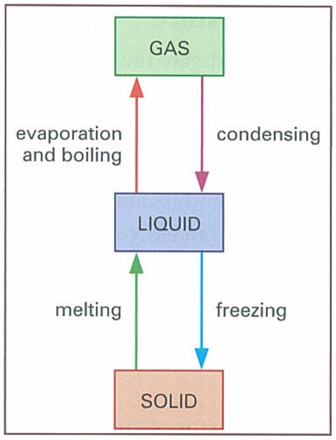


Figure 9.2 Naming changes of state.

Figure 9.3 shows what happens if you take some ice from the deep freeze and heat it at a steady rate. In a deep freeze, ice is at a temperature well below its freezing point (0 °C). From the graph, you can see that the ice warms up to 0 °C, then remains at this temperature while it melts. Lumps of ice float in water; both are at 0 °C. When all of the ice has melted, the water's temperature starts to rise again. At 100 °C, the boiling point of water, the temperature again remains steady. The water is boiling to form steam. This takes longer than melting, which tells us that it takes more energy to boil the water than to melt the ice. Eventually, all of the water has turned to steam. If we can continue to heat it, its temperature will rise again.

Notice that energy must be supplied to change a solid into a liquid. At the same time, its temperature remains constant as it melts. Similarly, when a liquid becomes a gas, its temperature remains constant even though energy is being supplied to it.

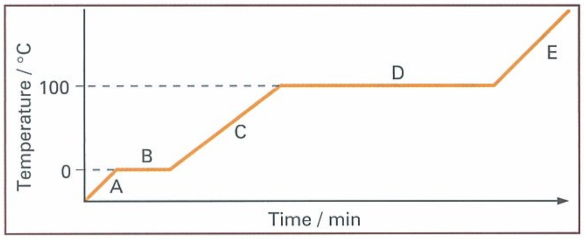


Figure 9.3 A temperature against time graph to show the changes that occur when ice is heated until it eventually becomes steam.

Investigating a change of state

Figure **9.4a** shows one way to investigate the behaviour of a liquid material as it solidifies. The test tube contains a waxy substance called octadecanoic acid. This is warmed up, and it becomes a clear, colourless liquid. It is then left to cool down, and its temperature is monitored using a thermometer (an electronic temperature probe) and recorded using a data-logger. The graph of Figure **9.4b** shows the results. From the graph, you can see that there are three stages in the cooling of the material.

1 The liquid wax cools down. Its temperature drops gradually. The wax is hotter than its surroundings, so it loses heat. Notice that the graph is slightly curved; this is because, as the temperature drops, there is less difference between the temperature of the wax and its surroundings, so it cools more slowly.

2 Now the wax's temperature remains constant for a few minutes. The tube can be seen to contain a mixture of clear liquid and white solid – the wax is solidifying. During this time, the wax is still losing heat, because it is still warmer than its surroundings, but its temperature does not decrease. This is an important observation that needs explaining.

3 The wax's temperature starts to drop again. It is now entirely solid, and it continues cooling until it reaches the temperature of its surroundings.

From the horizontal section of the graph (stage 2) we can draw a horizontal line across to the temperature axis and find the substance's melting point.

From the experiment shown in Figure **9.4**, you can see that a pure substance changes from solid to liquid at a particular temperature, known as the **melting point**. Similarly, a liquid changes to a gas at a fixed temperature, its **boiling point**. Table **9.2** shows the melting and boiling points of some pure substances.

Substance	Melting point / °C	Boiling point / °C
helium	−272	−269
oxygen	−218	−183
nitrogen	−191	−177
mercury	−39	257
water	0	100
iron	2080	3570
diamond (carbon)	4100	5400
tungsten	3920	6500

Table 9.2 The melting and boiling points of some pure substances. Mercury is interesting because it is the only metal that is not solid at room temperature. Tungsten is a metal, and it has the highest boiling point of any substance. Helium has the lowest melting and boiling points of any element. In fact, helium will only solidify if it is compressed as well as cooled.

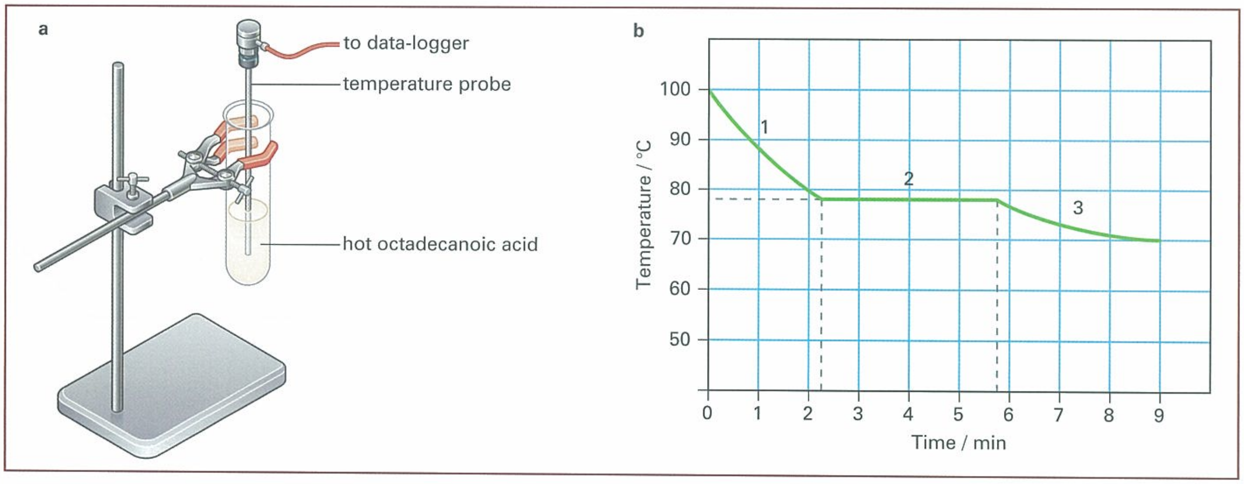


Figure 9.4 **a** As the warm liquid cools, its temperature is monitored by the electronic temperature probe. **b** The graph shows how the temperature of the octadecanoic acid drops as it cools. The temperature remains constant as the liquid solidifies.

Note that we have to be careful here to talk about **pure** substances. The temperature at which a substance melts or boils is different when another substance is dissolved in it. For example, salty water boils at a higher temperature than pure water, and freezes at a lower temperature. A mixture of substances may even melt or boil over a range of temperatures. Candle wax is an example. It is not a single, pure substance, and some of the substances in it melt at lower temperatures than others. Similarly, crude oil is a mixture of different substances, each with its own boiling point. You may have studied the process of fractional distillation, which is used to separate these substances (fractions) at an oil refinery.

There are other ways in which materials can behave when they are heated: some burn, and others decompose (break down) into simpler substances before they have a chance to change state.

Activity 9.1 Measuring melting point

Carry out an experiment to determine the melting point of octadecanoic acid or some other pure substance. Use the method shown in Figure **9.4**.

QUESTIONS

1 To measure the volume of a liquid, you can pour it into a measuring cylinder. Measuring cylinders come in different shapes and sizes – tall, short, wide, narrow. Explain why the **shape** of the cylinder does not affect the measurement of volume.

2 What name is given to the temperature at which a gas condenses to form a liquid?

3 **a** What name is given to the process in which a liquid changes into a solid?
  b What name is given to the temperature at which this happens?

4 **a** Look at Figure **9.3** on page **87**. What is happening in the section marked C?
  b Name the substance or substances present in the section marked D.

5 Look at Figure **9.4b**. From the graph, deduce the melting point of octadecanoic acid.

6 Table **9.2** shows the melting and boiling points of nitrogen and oxygen, the main constituents of air. Why can we not talk about the melting and boiling points of air?

9.2 The kinetic model of matter

Several questions arise from our discussion of changes of state. In this section, we will look at a model for matter that provides one way in which we can answer these questions:

- Why does it take time for a solid to melt? Why does it not change instantly into a liquid?
- Why does it take longer to boil a liquid than to melt a solid?
- Why do different substances melt at different temperatures?
- Why do different substances have different boiling points?

The model we are going to consider is called the **kinetic model of matter**. As we saw in Chapter **6**, the word ‘kinetic’ means ‘related to movement’. In this model, the things that are moving are the particles of which matter is made. The model thus has an alternative name: the **particle model of matter**.

The particles of which matter is made are very tiny. They may be atoms, molecules or ions, but we will simplify things by disregarding these differences and referring only to **particles**. We will also picture a material as consisting of large numbers of identical particles. Thus we are considering a pure substance whose particles are all the same, rather than a mixture that contains two or more types of particle. We will also picture the particles as simple spheres, although in reality they might have more complicated shapes. The molecules of a polymer, for example, may be like long thin strings of spaghetti, rather than like small, round peas.

The idea that matter is made up of spherical particles is a great simplification, but we can still use this idea to find answers to the questions listed above. Later, we will think about whether or not we are justified in using such a simplified model.

Arrangements of particles

Figure 9.5 shows how we picture the particles in a solid, a liquid and a gas. For each picture, we will think about two aspects (see Table 9.3): how the particles are arranged, and how the particles are moving. (Because these are pictures printed on paper, it is hard to represent the motion of the particles. You may have access to software or video images that can show this more clearly.)

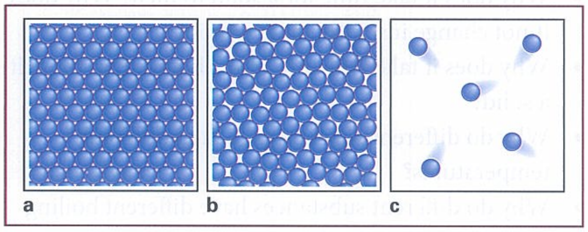


Figure 9.5 Representations of **a** solid, **b** liquid and **c** gas. The arrangement and motion of the particles change as the solid is heated to become first a liquid and then a gas.

Evidence for the kinetic model

We cannot look down a microscope and see the particles that make up matter. We certainly cannot hope to see the particles of a gas as they rush around. However, in the 1820s, the movement of the particles of a gas was investigated by a Scottish botanist, Robert Brown. He was using a microscope to study pollen grains when he noticed tiny particles jiggling about. At first he thought that they might be alive, but when he repeated his experiment with tiny grains of dust, suspended in water, he saw that they also moved around. This motion is now known as **Brownian motion**, and it happens because the moving particles are constantly buffeted by the fast-moving particles of the air.

Today, we can perform a similar experiment using smoke grains. The oxygen and nitrogen molecules that make up the air are far too small to see, so we have to look at something bigger, and look for the effect of the air molecules. We use a smoke cell (Figure 9.6), which contains air with a small amount of smoke. The cell is lit from the side, and the microscope is used to view the smoke grains.

The smoke grains show up as tiny specks of light, but they are too small to see any detail of their shape.

State	Arrangement of particles	Movement of particles
solid	The particles are packed closely together. Notice that each particle is in close contact with all of its neighbours. In a solid such as a metal, each atom may be in contact with 12 neighbouring atoms.	Because the particles are so tightly packed, they cannot move around. However, they do move a bit. They are able to vibrate about a fixed position. The hotter the solid, the more they vibrate.
liquid	The particles are packed slightly less closely together (compared with a solid). Each particle is still in close contact with most of its neighbours, but fewer than in the case of a solid. The general arrangement is slightly more jumbled and disorderly.	Because the particles are slightly less tightly packed than in a solid, they have the opportunity to move around within the bulk of the liquid. Hence the particles are both vibrating and moving from place to place.
gas	Now the particles are widely separated from one another. They are no longer in contact, unless they collide with each other. In air, the average separation between the particles is about ten times their diameter.	The particles are now moving freely about, bouncing off one another and off the walls of their container. In air at room temperature, their average speed is about 400 m/s.

Table 9.3 The arrangement and movement of particles in the three different states of matter. Compare these statements with the pictures shown in Figure **9.5.**

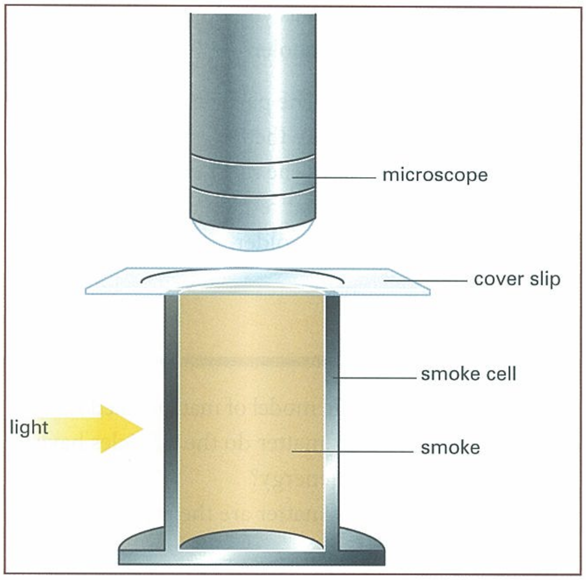


Figure 9.6 An experimental arrangement for observing Brownian motion. The grains of smoke are just large enough to show up under the microscope. The air molecules that collide with them are much too small to see.

What is noticeable is the way they move. If you can concentrate on a single grain, you will see that it follows a somewhat jerky and erratic path. This is a consequence of the grain suffering repeated collisions with air molecules.

Observing Brownian motion of smoke or pollen grains does not mean that we have proved that air and water are made of moving particles. We have not seen the particles themselves. Observing Brownian motion is rather like watching a hockey match from an aircraft high overhead. You may see the players rushing around, but you cannot see the ball. Careful observation over a period of time might lead you to guess that there was a ball moving around among the players, and eventually you might work out the rules of hockey.

However, the kinetic model does give a satisfying explanation of Brownian motion. Much of what scientists have learned since Brown did his first experiments has confirmed his suggestion that he had discovered an effect caused by moving molecules.

Observing Brownian motion of smoke particles in air allows us to deduce something important about the motion of air molecules. The air molecules are much smaller than the smoke grains – in other words, they are very light, compared to smoke grains – and yet they can cause the smoke grains to move around. The air molecules can only do this if they are moving around very fast. In fact, the molecules of the air around us move at speeds of the order of 500 m/s – that is a little faster than the speed of sound in air.

Activity 9.2 Observing Brownian motion

Watch brightly lit smoke grains moving in air. You may also be able to watch a video of Brownian motion.

Explanations using the kinetic model

The kinetic model of matter can be used to explain many observations. Here are some:

- Liquids take up the shape of their container, because their particles are free to move about within the bulk of the liquid.
- Gases fill their container, because their particles can move freely about.
- Solids retain their shape, because the particles are packed tightly together.
- Gases diffuse (spread out) from place to place, so that, for example, we can smell perfume across the room. The perfume particles spread about because they are freely mobile.
- Similarly, dissolved substances diffuse throughout a liquid. Sugar crystals in a drink dissolve and molecules spread throughout the liquid, carried by the mobile particles. In a hotter drink, the particles are moving faster and the sugar diffuses more quickly.
- Most solids expand when they melt. The particles are slightly further apart in a liquid than in a solid.
- Liquids expand a lot when they boil. The particles of a gas are much farther apart than in a liquid. We can think about this the other way round. Gases contract a lot when they condense. If all of the air in the room you are now in was cooled enough, it would condense to form a thin layer of liquid, two or three millimetres deep, on the floor.

Evaporation

The boiling point of water is 100 °C, but water does not have to be heated to 100 °C before it will turn into a gas. After a downpour of rain, the puddles eventually dry up even though the temperature is much lower than 100 °C. We say that the water has become water vapour in the air. This is the process of **evaporation**. We can think of a vapour as a gas at a temperature below its boiling point.

A liquid evaporates more quickly as its temperature approaches its boiling point. That is why puddles disappear quickly after a storm in the tropics, where the temperature may be 30 °C, but they may lie around for days in a cold region, where the temperature is close to 0 °C.

How can we use the kinetic model of matter to explain evaporation? Picture a beaker of water. The water will gradually evaporate. Figure 9.7 shows the particles that make up the water. The particles of the water are moving around, and some are moving faster than others. Some may be moving fast enough to escape from the surface of the water. They become particles of water vapour in the air. In this way, all of the water particles may eventually escape from the beaker, and the water has evaporated.

If you get wet, perhaps because you are caught in the rain or you have been swimming, you will notice that you can quickly get cold. The water on your body is evaporating, and this cools you down. Why does evaporation make things cooler?

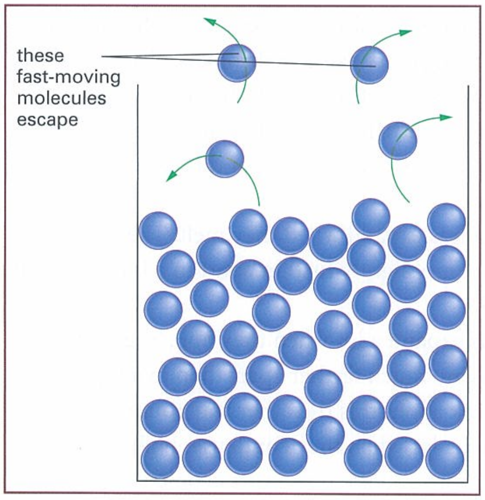


Figure 9.7 Fast-moving particles leave the surface of a liquid – this is how it evaporates.

Look again at Figure 9.7. The particles that are escaping from the water are the fastest-moving ones. They are the particles with the most energy. This means that the particles that remain are those with less energy, and so the water is colder.

QUESTIONS

7 a Why is the kinetic model of matter called **kinetic**?
  b In which state of matter do the particles have the most kinetic energy?

8 a In which state of matter are the particles most closely packed?
  b In which state of matter are they most widely separated?

9 Use the kinetic model of matter to explain why we can walk through air and swim through water but we cannot walk through a solid wall.

10 In an experiment to observe Brownian motion, a student watched a brightly lit grain of dust moving around in water, following a random path.
  a Explain why the student could not see the molecules of the water moving around.
  b Explain why the grain of dust moved around in the water.

9.3 Forces and the kinetic theory

So far, we have seen how the kinetic theory of matter can successfully explain some observations of the ways in which solids, liquids and gases differ. We can explain some other observations if we add another scientific idea to the kinetic theory: we need to consider the forces between the particles that make up matter.

Why do the particles that make up a solid or a liquid stick together? There must be **attractive forces** between them. Without attractive forces to hold together the particles that make up matter, we would live in a very dull world. There would be no solids or liquids, only gases. No matter how much we cooled matter down, it would remain as a gas.

Another way to refer to these forces is to say that there are **bonds** between the particles. Each particle of a solid is strongly bonded to its neighbours. This is because the forces between particles are strongest when the particles are close together. In a liquid, the particles are slightly further apart and so the forces between them are slightly weaker. In a gas, the particles are far apart, so that the particles do not attract each other and can move freely about.

Kinetic theory and changes of state

What happens to these attractive forces as a solid is heated? The particles start to vibrate more and more strongly. Eventually, the particles vibrate sufficiently for some of the bonds to be broken, and a liquid is formed. Heat the material more and eventually the particles have sufficient energy for all of the attractive forces between particles to be overcome. The material becomes a gas.

In a gas, the particles are so far apart and moving so fast that they do not stick together. If you cool down a gas (Figure **9.8**), the particles move more slowly. As they collide with one another, there is more chance that they will stick together. Keep cooling the gas and eventually all of the particles stick together to form a liquid.

More about evaporation

Evaporation is different from boiling. A liquid boils at its boiling point – all of the liquid reaches this temperature and it gradually turns into a gas. Evaporation happens at a lower temperature, below the boiling point.

We have seen (page **92**) that the kinetic model can explain why a liquid cools as it evaporates, because it is the most energetic particles that are leaving its surface. We can use the kinetic model to explain some more observations concerning evaporation (see Table **9.4**).

Observation	Explanation
A liquid evaporates more rapidly when it is hotter.	At a higher temperature, more of the particles of the liquid are moving fast enough to escape from the surface.
A liquid evaporates more quickly when it is spread out, so that it has a greater surface area.	With a greater surface area, more of the particles are close to the surface, and so they can escape more easily.
A liquid evaporates more quickly when a draught blows across its surface.	A draught is moving air. When particles escape from the water, they are blown away so that they cannot fall back in to the water.

Table 9.4 Evaporation – observations and explanations.

Activity 9.3 Using the kinetic model

Discuss how the kinetic model can explain some observations.

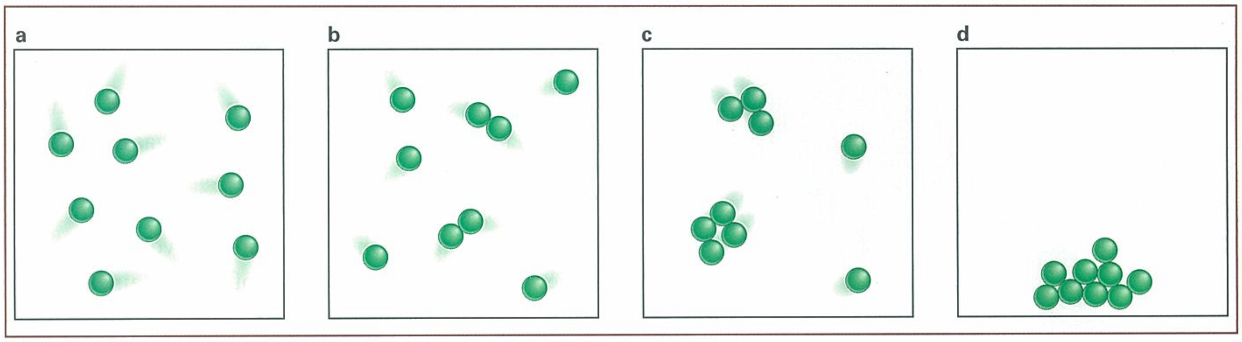


Figure 9.8 **a** As a gas is cooled, it starts to condense. **b** The particles move more slowly and they start to stick together, because of the attractive forces between them. **c** As their energy gets less, they clump together in bigger and bigger groups. **d** Finally, they form a liquid.

E

QUESTIONS

11 Tungsten melts at a much higher temperature than iron. What can you say about the forces between the tungsten atoms, compared to the forces between the iron atoms?

12 A particular solid material is heated but its temperature does not rise.
   a What is happening to the solid?
   b Where does the energy go that is being supplied to it?

13 If a gas is heated, its molecules move faster. Use the kinetic model to make a prediction: What will happen to the pressure that a gas exerts on the walls of its container when the gas is heated?

9.4 Gases and the kinetic theory

We can understand more about gases if we think about the particles of which they are made. For example:

- Why does a gas exert pressure?
- What happens to a gas when it is heated?
- What happens when a gas is compressed?

If you blow up a balloon (Figure 9.9), your lungs provide the pressure to push the air into it. Tie up the balloon and the air is trapped. The pressure of the air inside pushes outwards against the rubber, keeping it inflated. The more air you blow into the balloon, the greater its pressure.

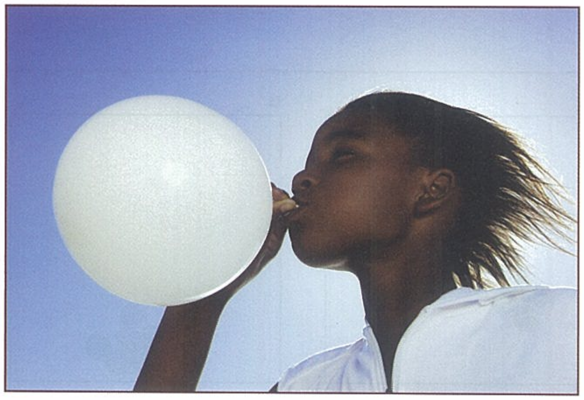


Figure 9.9 Inflating a balloon – as you blow, the pressure of the air inside the balloon increases.

Figure **9.10a** shows the particles that make up a gas. The gas is contained in a square box. The volume of the box is the volume of the gas. The gas has mass because each of its particles has mass. If we weighed all the particles individually and added up their masses, we would find the mass of the gas.

Figure **9.10b** shows the same box with twice as many gas particles in it. The mass of the gas is doubled, and so is its density.

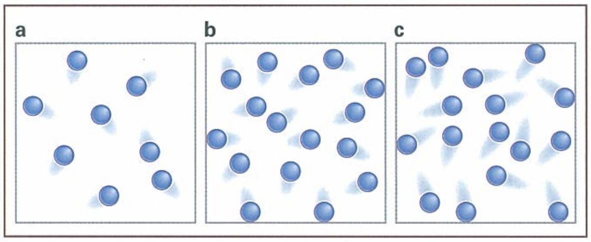


Figure 9.10 **a** The particles of a gas move around inside its container, bumping into the sides. **b** Doubling the number of particles means twice the mass, twice the density and twice the pressure. **c** At a higher temperature, the particles move faster. They have more kinetic energy, and this is what a thermometer records as a higher temperature.

A gas exerts pressure on the walls of its container because its particles are constantly colliding with the walls. They bounce off the walls, exerting a force as they do so. Compare Figures **9.10a** and **9.10b**: with twice as many particles, there are twice as many collisions, so the pressure is doubled.

Figure **9.10c** shows the same gas at a higher temperature. The particles are moving faster, and as a result they have more kinetic energy. So the higher the temperature of a gas, the faster its particles are moving.

Compressing a gas

Figure **9.11** shows some gas trapped in a box. If the box is made smaller, the volume of the gas decreases. At the same time, its pressure increases. From the diagram, you can see why this is. The particles of the gas have been squashed into a smaller volume. So they will collide with the walls of the container more frequently, creating an increased pressure. If the gas is compressed to half its original volume, its pressure will be doubled.

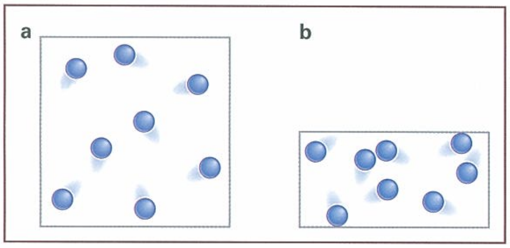


Figure 9.11 With the same number of particles in half the volume, in **b** there are twice as many collisions per second with the walls of the container. The result is twice the pressure in **b** as in **a**.

QUESTIONS

14 Look at Figure **9.10a**. If half of the particles of the gas were removed from the container (and nothing else was changed), how would the following properties of the gas change?

a density **b** pressure **c** temperature

15 Draw diagrams of the particles in a gas to explain why, if the volume of the gas is doubled, its pressure is halved.

16 Look at Figure **9.11**. The gas in **b** has twice the pressure as the gas in **a**. How could you change the temperature of the gas in **b** so that its pressure would be the same as that of the gas in **a**? Explain your answer.

Boyle's law

Figure **9.12** shows a method for investigating what happens when the pressure on a fixed mass of gas is increased. In this apparatus, some air is trapped inside the vertical glass tube. The oil in the bottom of the apparatus can be compressed with a pump, so that it pushes up inside the tube, compressing the air. The volume of the air can be read from the scale. The pressure exerted on it by the oil can be read from the dial gauge.

Increasing the pressure on the gas decreases its volume. Table **9.5** shows some typical results. But can we find a mathematical relationship between the pressure p and the volume V of the gas?

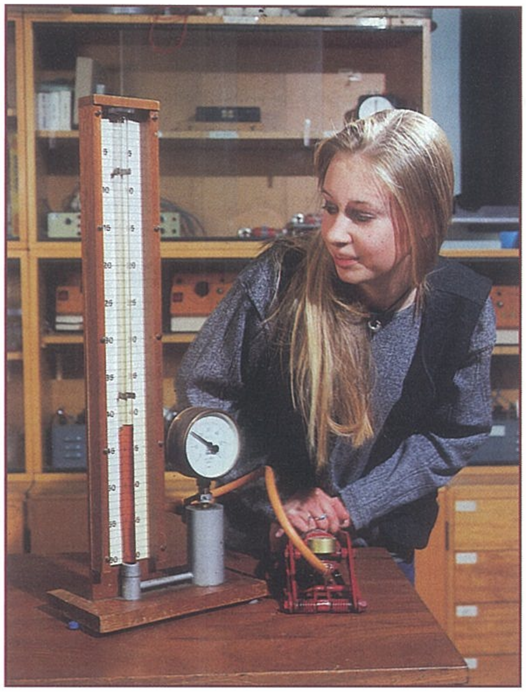


Figure 9.12 Apparatus for increasing the pressure on a gas. A fixed mass of air is trapped inside the tube, and the pressure on it is increased.

Pressure, p / Pa	Volume, V / cm^3	Pressure × volume, pV / Pa cm^3
100	60	6000
125	48	6000
150	40	6000
200	30	6000
250	24	6000
300	20	6000

Table 9.5 Representative results for a Boyle's law experiment, to show their pattern. The temperature of the gas remains constant throughout.

The relationship between p and V was investigated by Robert Boyle, an English physicist and chemist. He published his results in 1662.

The relationship that Boyle found can be stated in a number of different ways:

1 Doubling the pressure has the effect of halving the volume. Three times the pressure gives one-third of the volume, and so on.
2 The graph of Figure **9.13a** shows that increasing pressure leads to decreasing volume.
3 The numbers in Table **9.5** also show this relationship. From the last column in the table, we can see that the quantity pressure × volume is constant, so we can write

$$pV = \text{constant}$$

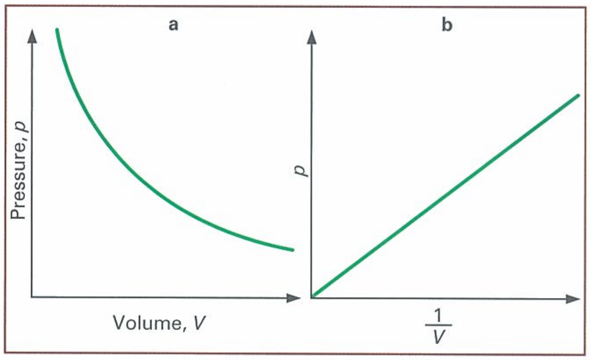


Figure 9.13 Two graphs to represent the results of a Boyle's law experiment. **a** The graph of pressure against volume shows that increasing the pressure causes a decrease in the volume. **b** The mathematical relationship between p and $1/V$ can be seen from this graph. Since it is a straight line through the origin, we can say that pressure is inversely proportional to volume (and vice versa).

4 We can write the same idea in a way that is convenient for doing calculations:

initial pressure × initial volume
= final pressure × final volume

or

$$p_1V_1 = p_2V_2$$

where p_1 and V_1 are one pair of readings of pressure and volume, and p_2 and V_2 are another pair. This equation is easy to memorise, and we shall make use of it in Worked example **1**.

5 If one quantity decreases like this as another increases, we say that one is **inversely proportional** to the other. Using the symbol ∝ ('is proportional to'), we can write

$$p \propto \frac{1}{V} \qquad \text{or} \qquad V \propto \frac{1}{p}$$

6 The graph of Figure **9.13b** shows that plotting p against $1/V$ gives a straight-line graph, passing through the origin.
7 Finally, we can write the relationship in words:

The volume of a fixed mass of gas is inversely proportional to its pressure, provided its temperature remains constant.

This statement is known as **Boyle's law**.

It is important to understand why Boyle's law includes the phrase 'provided its temperature remains constant'. When a gas is compressed, its temperature rises (because energy is being transferred to the gas), and this tends to make it expand. In the Boyle's law experiment, the trapped air soon loses energy to its surroundings and cools back down to room temperature. While it is hot, its volume is increased. Only when it cools down will we find that it obeys the relationship pV = constant.

Worked example 1 shows how to use the equation $p_1V_1 = p_2V_2$ to find how the volume of a gas changes when the pressure on it is changed. You can use the same equation to work out how the pressure changes when the volume is changed.

Worked example 1

A cylinder contains 50 cm^3 of air at a pressure of 120 kPa. What will its volume be if the pressure on it is increased to 400 kPa?

Step 1: Write down the initial and final values of the quantities that we know.

$p_1 = 120\,\text{kPa}$
$V_1 = 50\,\text{cm}^3$
$p_2 = 400\,\text{kPa}$
$V_2 = ?$

Step 2: Write down the Boyle's law equation and substitute values.

$$p_1V_1 = p_2V_2$$

$$120\,\text{kPa} \times 50\,\text{cm}^3 = 400\,\text{kPa} \times V_2$$

Step 3: There is only one unknown quantity in this equation (V_2). Rearrange it and solve.

$$V_2 = \frac{120\,\text{kPa} \times 50\,\text{cm}^3}{400\,\text{kPa}} = 15\,\text{cm}^3$$

So the volume of the air is reduced to 15 cm^3 when it is compressed.

Notice an important feature of the equation $p_1V_1 = p_2V_2$. It does not matter what units we use for p and V, as long as we use the same units for both values of p (for example, Pa or kPa), and the same units for both values of V (for example, m^3, dm^3, or cm^3). In Question **19**, you are asked to use units that you may not be familiar with: atmospheres for pressure, and litres for volume.

Activity 9.4 Pressure and volume of a gas

Solve some problems involving Boyle's law.

QUESTIONS

17 What is the meaning of the subscripts 1 and 2 in the equation $p_1V_1 = p_2V_2$?

18 The pressure on 6 dm^3 of nitrogen gas is doubled at a fixed temperature. What will its volume become?

19 A container holds 600 litres of air at a pressure of 2 atmospheres. If the pressure on the gas is increased to 5 atmospheres, what will its volume become? (Assume that the temperature remains constant.)

20 A gas cylinder has a volume of 0.4 m^3. It contains butane at a pressure of 100 kPa and a temperature of 20 °C. What pressure is needed to compress the gas to a volume of 0.05 m^3 at the same temperature?

Summary

According to the kinetic model, matter is made of moving particles that are close together in solids and liquids, and far apart in gases.

There are attractive forces between particles that act strongly at short distances.

In Brownian motion, the movement of water or air molecules is revealed by their effect on visible grains of pollen or smoke.

As the temperature of a substance increases, the kinetic energy of its particles increases.

During a change of state, energy is supplied but the temperature of a pure substance remains constant.

When a liquid evaporates, the most energetic of its particles escape from the surface so that the liquid cools.

Evaporation occurs at temperatures below the boiling point. It happens faster at higher temperatures, when the surface area is large and when there is a draught.

When the pressure applied to a gas is increased, its volume decreases (at constant temperature).

Pressure and volume are related by pV = constant.

End-of-chapter questions

9.1 For each of the following statements, name the state of matter being described:

- **a** Expands to fill the volume of its container. [1]
- **b** Has a fixed size and shape. [1]
- **c** Has a fixed volume but takes up the shape of its container. [1]

9.2 **a** 'The particles are packed closely together. They can vibrate about their fixed positions but they cannot move about within the material.' Which state of matter is being described here? [1]

b Write a similar description of the particles that make up a gas. [2]

9.3 A small amount of smoke is blown into a small glass box. A bright light is shone into the box. When observed through a microscope, specks of light are seen to be moving around at random in the box.

- **a** What are these bright specks of light? [1]
- **b** What evidence does this provide for the kinetic model of matter? [2]

9.4 A student pours a small amount of ethanol into a beaker. She places the beaker on an electronic balance to find its mass, and adds a thermometer to measure the temperature of the liquid. Two hours later, she returns to her experiment. She notices that the mass of the beaker and its contents has decreased. She can also see that the temperature of the ethanol has decreased. She guesses that some of the ethanol has evaporated from the beaker.

- **a** Describe how evaporation can explain the decrease in mass. [2]
- **b** Describe how evaporation can explain the decrease in temperature. [3]

9.5 These questions concern the behaviour of gases.

- **a** A rigid container holds a fixed volume of air. The container is heated. How will the pressure of the air change? [1]
- **b** A container is fitted with a piston that allows the pressure on the air in the container to be changed. The piston is pulled outwards so that the volume of the air increases. How will the pressure of the air change? [1]

E

9.6 A small container of water is placed in an oven at 90 °C. The water soon disappears.

- **a** What name is given to process by which a liquid becomes a gas at a temperature below its boiling point? [1]
- **b** Why must energy be supplied to a liquid to turn it into a gas? In your answer, refer to the particles of the liquid and the forces between them. [2]

9.7 A container holds $20\,\mathrm{m}^3$ of air at a pressure of 120 000 Pa. If the pressure is increased to 160 000 Pa, what will the volume of the gas become? Assume that its temperature remains constant. [3]

10 Thermal properties of matter

Core	Measuring temperature
Core	Understanding and using thermometers
E **Extension**	Designing thermometers
Core	Describing the thermal expansion of solids, liquids and gases
Core	Explaining some uses and consequences of thermal expansion
Core	Relating energy supplied to rise in temperature when a body is heated
E **Extension**	Measuring specific heat capacity

Measuring temperature

When someone is about to bath a baby, she or he fills a tub with water and then checks its temperature. This may be done by dipping an elbow into the water (Figure **10.1**). The elbow is sensitive to temperature. If the water feels too hot, adding cold water can cool it to the desired temperature.

The person wants the water to be at body temperature, about 37 °C. She or he is using the fact that there are nerve endings in the skin that are sensitive to temperature. When the water feels neither hot nor cold, it is at the right temperature.

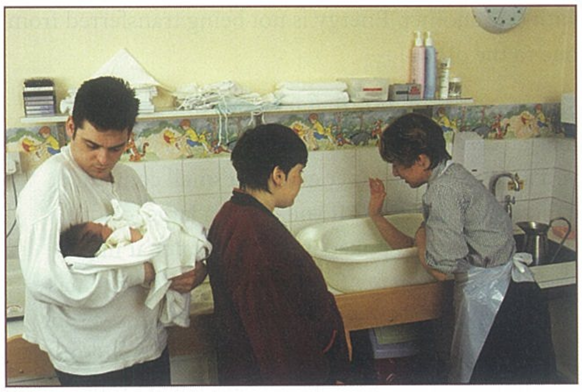


Figure 10.1 The midwife is showing the new-born baby's parents how to check the temperature of the bath water.

If someone is ill, he or she may have a temperature. Another person can test this by touching the ill person's forehead to try to detect a difference in temperature between him- or herself and the ill person. This may seem rather unscientific, but it works!

In science, we use thermometers for measuring temperature. Figure **10.2** shows two thermometers being used to measure human body temperature. One is a liquid-in-glass thermometer (Figure **10.2a**), in which a thin column of mercury expands inside an evacuated glass tube as it gets hotter. The other is a liquid-crystal thermometer (Figure **10.2b**), in which each segment shows up at a particular temperature. This latter type is much safer, particularly for use with children, who might bite and break a glass thermometer.

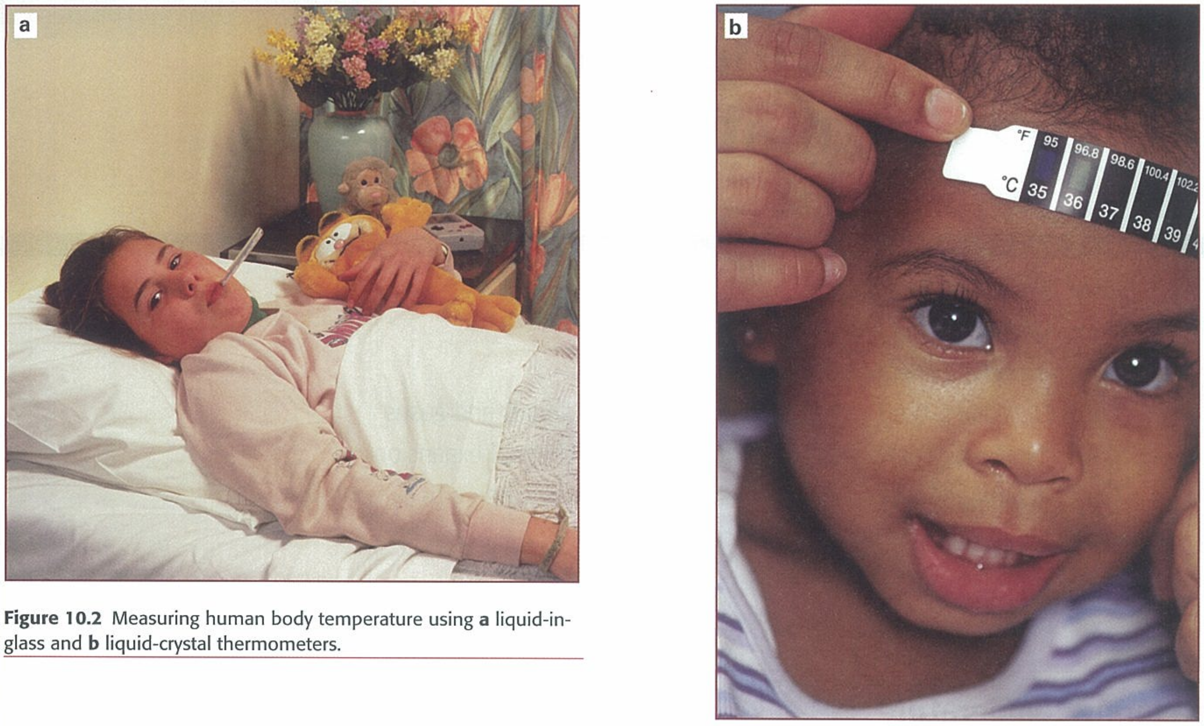


Figure 10.2 Measuring human body temperature using **a** liquid-in-glass and **b** liquid-crystal thermometers.

10.1 Temperature and temperature scales

With both of the thermometers shown in Figure **10.2**, it is important to wait for a minute or two if you want to see the correct reading. This is because the thermometer has probably been stored somewhere relatively cool, perhaps in a drawer at 20 °C. The patient's temperature will be approximately 37 °C, and it takes a short while for the thermometer to reach this temperature.

This gives us an idea of what we mean by **temperature**. The thermometer is placed in contact with the patient's body. It has to warm up until it reaches the same temperature as the patient. Energy from the patient is shared with the thermometer until they are at the same temperature. Then you will get the correct reading. (So the thermometer does not tell you the patient's temperature – it tells its own temperature! However, we know that the patient's temperature is the same as the thermometer's.)

Figure **10.3** shows a thermometer measuring the temperature of some hot water. The molecules of the water are rushing about very rapidly, because the water is hot. They collide with the thermometer and share their energy with it. The bulb of the thermometer gets hotter. Eventually, the thermometer bulb is at the same temperature as the water. (We say that the water and the thermometer bulb are in **thermal equilibrium** with one another. Energy is not being transferred from one to the other.)

You can see from this that it can be important to make a careful choice of thermometer. How could you measure the temperature of a small container containing hot water? If you chose a large, cold thermometer and poked it into the water, it might absorb a lot of energy from the water and thus make it much cooler. You would get the wrong answer for the temperature. A better solution might be to use an electronic thermometer with a very small probe. This would absorb less of the energy of the water.

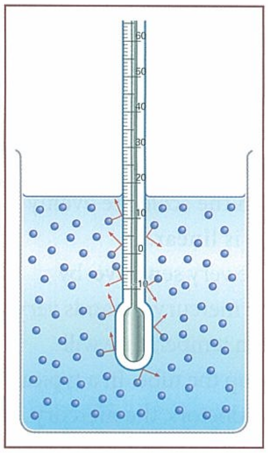


Figure 10.3 A thermometer placed in hot water is bombarded by the fast-moving water molecules. It absorbs some of their energy. Eventually, it reaches the same temperature as the water and gives the correct reading.

Temperature and internal energy

A thermometer thus tells us about the average energy of the particles in the object whose temperature we are measuring. It does this by sharing the energy of the particles. If they are moving rapidly, the thermometer will indicate a higher temperature. Placing a thermometer into an object to measure its temperature is rather like putting your finger into some bath water to detect how hot it is. Your finger does not have a scale from 0 to 100, but it can tell you how hot or cold the water is, from uncomfortably cold to comfortably warm to painfully hot.

Thus the temperature of an object is a measure of the **average kinetic energy** of its particles. Because it is the *average* kinetic energy of a particle, it does not depend on the size of the object. We can compare internal energy and temperature:

- **internal energy** is the **total** energy of **all** of the particles
- **temperature** is a measure of the **average kinetic** energy of the **individual** particles.

So a bath of water at 50 °C has more internal energy than a cup of water at the same temperature, but its individual molecules have the same average kinetic energy as the molecules of the water in the cup.

The Celsius scale

Galileo is credited with devising the first thermometer, in 1593 (Figure **10.4**). The air inside the flask expanded and contracted as the temperature rose and fell. This made the level of the water in the tube change. This could only indicate changes in temperature over a narrow range, and proved unsatisfactory because water evaporated from the reservoir. Galileo knew that air expands as its temperature increases. Modern liquid-in-glass thermometers use mercury or alcohol instead of air. These are also substances that expand when they are heated.

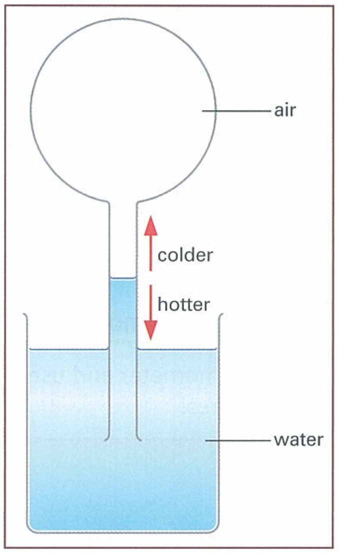


Figure 10.4 The idea behind Galileo's thermometer, the first of all thermometers. It had only a narrow operating range and no scale. As water evaporated and air dissolved in the water, the reading became unreliable.

Anders Celsius, working in Sweden, devised a more successful thermometer than Galileo's. It had a volume of mercury in an enclosed and evacuated tube, with no chance of liquid loss by evaporation. It was like the much more modern Celsius thermometer shown in Figure **10.5**. Celsius also devised a scale of temperature, now known as the Celsius scale. This had two **fixed points**:

- 0 °C – the freezing point of pure water at atmospheric pressure
- 100 °C – the boiling point of pure water at atmospheric pressure.

Each time he made a new thermometer, Celsius could calibrate it quite simply by putting it first into melting ice and then into boiling water, marking the scale each time. Then he could divide the scale into 100 equal divisions. This process is known as **calibration** of the thermometer. (It is interesting to note that, with his first thermometers, Celsius marked the boiling point of water as 0 degrees and the freezing point as 100 degrees. It was a few years later that one of his collaborators decided that it was better to have the scale the other way up.)

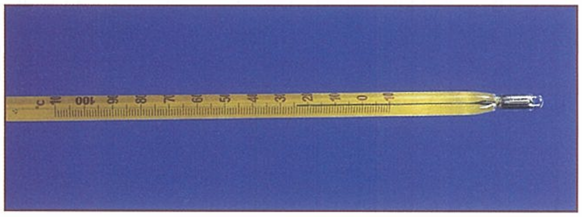


Figure 10.5 A modern Celsius-scale liquid-in-glass thermometer, with a fixed quantity of mercury sealed in a glass tube.

Activity 10.1 Calibrating a thermometer

Mark the scale on a blank thermometer and use it to measure some temperatures.

QUESTIONS

1 Two buckets contain water at 30 °C. One contains 1 kg of water, and the other contains 2 kg of water. State and explain whether the following quantities are the same or different for the water in the two buckets:

 a internal energy

 b temperature

 c average energy of a molecule.

2 What are the **two** fixed points on the Celsius scale?

3 Write step-by-step instructions for the calibration of a thermometer using the Celsius scale.

Designing a thermometer

Mercury-in-glass (and alcohol-in-glass) thermometers are used in many different situations. They are attractive for a number of reasons:

- Mercury expands at a steady rate as it is heated. This means that the marks on the scale are evenly spaced. We say that the scale is **linear**.
- The thermometer can be made very **sensitive**, by making the tube up which the mercury expands very narrow. Then a small change in temperature will push the mercury a long way up the tube. In a typical clinical thermometer, used by doctors, the mercury rises several millimetres for a 1 °C rise in temperature. This makes it possible to measure small changes.
- A mercury thermometer can have a wide **range**, because mercury is liquid between −39 °C and +350 °C. Some domestic ovens have mercury thermometers that read up to 250 °C.

The problem with mercury thermometers is that they have to be read by eye. An alternative is to use an electronic thermometer. Some of these are based on **thermistors**, which are resistors whose resistance changes by a large amount over a narrow temperature range (see Figure **10.6**). These can be very useful, especially as they are robust and can be built into electronic circuits.

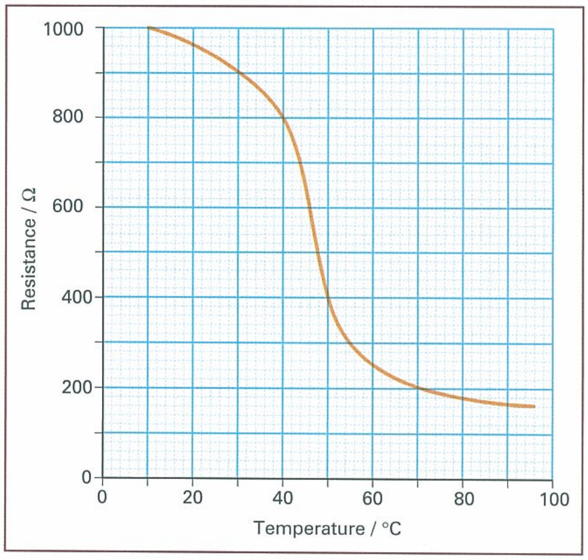


Figure 10.6 The electrical resistance of a thermistor changes over a narrow range of temperatures. This means that it can be used as a temperature probe for an electronic thermometer. However, it will only be sensitive over a narrow range, and its behaviour may be non-linear.

However, from the graph in Figure **10.6**, you can see the following:

- The resistance of a thermistor changes in a non-linear way, so that the intervals on a scale will not all be equal in size.
- The range of such a thermometer will be narrow, because the resistance only changes significantly over a narrow range of temperatures. You would need to choose a thermistor whose resistance changes most near the temperature you were trying to measure if you want the thermometer to be sensitive.

A second alternative is to use a **thermocouple**, a device that gives an output voltage that depends on the temperature. Thermocouples are made from pieces of wire made from two different metals. A wire of metal X is joined at each end to wires of metal Y to form two junctions. To use the thermocouple, its ends are connected to a sensitive voltmeter (see Figure **10.7**). Then one junction is placed in melting ice at 0 °C while the other is placed in the object whose temperature is to be measured. The voltmeter shows a reading. The greater the voltage produced, the bigger the difference in temperatures between the two junctions. The thermocouple must be calibrated so that the temperature can be deduced from the voltage.

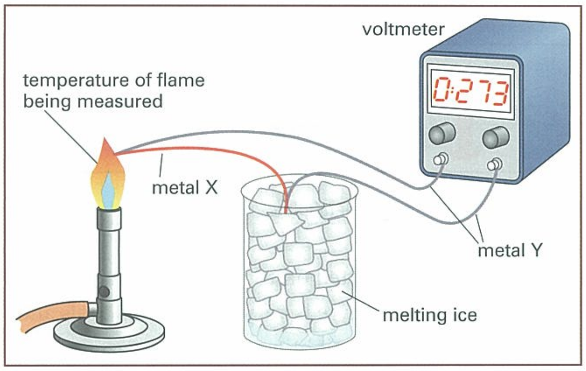


Figure 10.7 Using a thermocouple to measure temperature.

Many electronic thermometers make use of thermocouples (Figure **10.8**). The junctions of a thermocouple thermometer can be very small, so that they are robust, and they do not absorb much energy from the material whose temperature they are measuring. Some combinations of metals give bigger voltages than others, so it is important to choose them carefully.

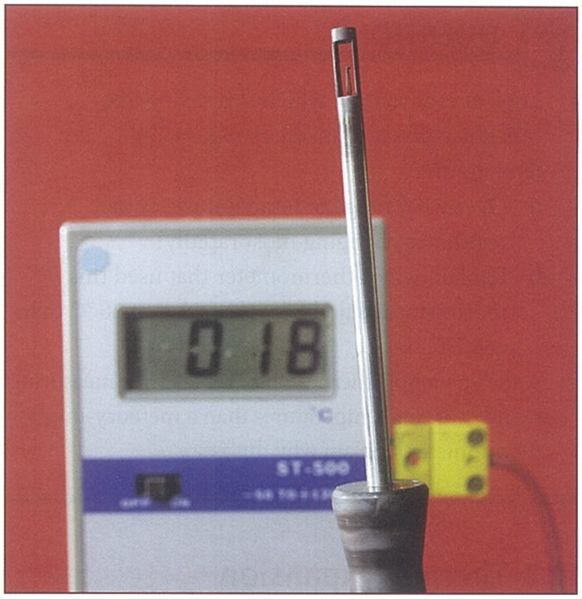


Figure 10.8 This electronic thermometer uses a thermocouple as its probe. You may just about be able to see the thin wires that make up the junction (in the 'eye' of the device). These are connected to a box with electronic circuits that convert the voltage produced to a digital temperature reading.

Thermocouples can be used to measure high temperatures (up to the melting point of the metal used). Because they are small, they can heat up and cool down quickly, so they are useful for measuring rapidly varying temperatures.

Thermocouples are used in many gas ovens and heaters that have a pilot flame that burns continuously. One junction is positioned in the flame, giving a voltage of about 20 mV. If the pilot flame goes out, the voltage drops and an electric circuit turns off the gas supply to the burners and the pilot flame.

Activity 10.2 Understanding thermometers

Answer some questions about the design of thermometers.

E

QUESTIONS

4 Look at Figure **10.6**, which shows how the resistance of a thermistor changes with temperature.
  a Over what range of temperatures is the resistance changing most rapidly?
  b Explain why a thermometer that used this thermistor would be less sensitive at 20 °C than at 50 °C.

5 A thermocouple thermometer is better for measuring rapidly varying temperatures than a mercury-in-glass thermometer. Explain why this is so.

10.2 Thermal expansion

Most substances – solids, liquids and gases – expand when they are heated. This is called **thermal expansion** (the word 'thermal' means 'related to heat'). We have already seen that some types of thermometer make use of the thermal expansion of a liquid. Figure **10.9** shows an experiment that demonstrates that a metal bar expands when heated.

- When it is cold, the iron bar will just fit in the gap in the measuring device.
- The bar (but not the measuring device) is heated strongly. Now it is too long to fit in the gap – it has expanded.
- When it cools down, the bar contracts and returns to its original length.

Uses of expansion

Rivets are used in shipbuilding and other industries to join metal plates. A red-hot rivet is passed through holes in two metal plates and then hammered until the ends are rounded (Figure **10.10**). As the rivet cools, it contracts and pulls the two plates tightly together.

A metal lid or cap may stick on a glass jar or bottle. Heating the lid (for example, by running hot water over it) causes it to expand (the glass expands much less), so that the lid loosens and can be removed.

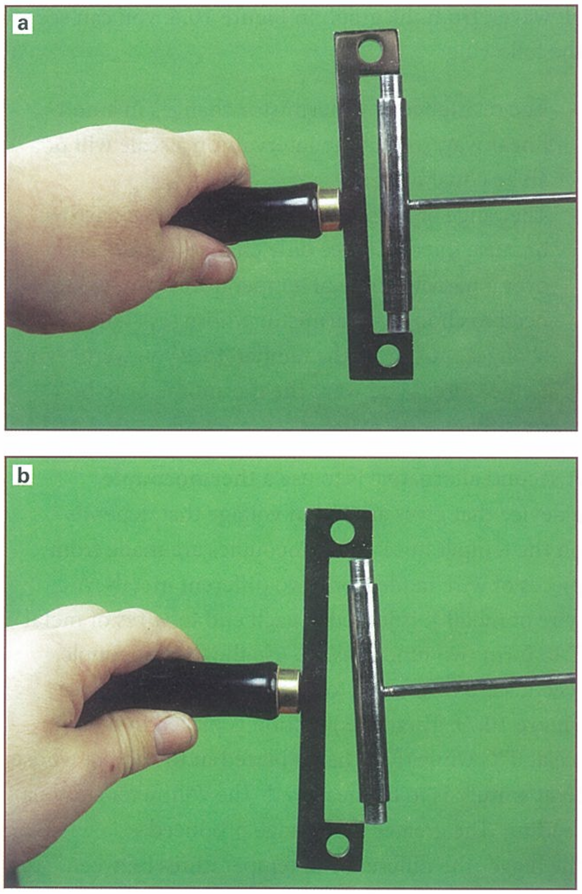


Figure 10.9 In **a**, the metal bar is cold, and fits in the gap in the measuring device. In **b**, it has been heated so that it expands and will no longer fit the gap.

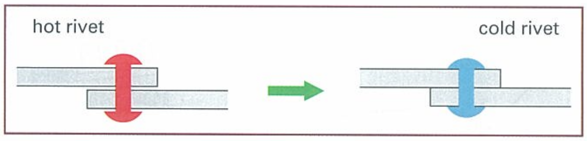


Figure 10.10 Joining two metal plates using a rivet.

A steel 'tyre' may be fitted on to the wheel of a railway locomotive while the tyre is very hot. It then cools and contracts, so that it fits tightly on to the wheel.

A bimetallic strip (Figure **10.11**) is designed to bend as it gets hot. The strip is made of two metals joined firmly together. One metal expands more rapidly than the other. As the strip is heated, this metal expands rapidly, causing the strip to bend. (The metal that expands more is on the outside of the curve, because the outer curve is longer than the inner one.) These strips are used in devices such as fire alarms and thermostats (which control the temperature of ovens, irons, water heaters, refrigerators, and so on).

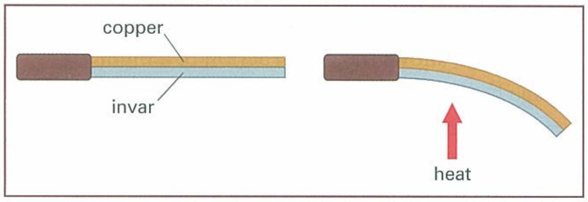


Figure 10.11 A bimetallic strip. 'Invar' is a metal alloy that expands very little when it is heated. Copper expands more readily when it is heated. This difference in expansion forces the strip to bend.

Consequences of expansion

The expansion of materials can cause problems. For example, metal bridges and railway lines expand on hot days, and there is a danger that they might buckle. To avoid this, bridges are made in sections, with expansion joints between the sections (Figure **10.12**). On a hot day, the bridge expands and the gaps between sections decrease. Railway lines are now usually made from a metal alloy that expands very little. On a concrete roadway, you may notice that the road surface is in short sections. The gaps between are filled with soft pitch, which becomes squashed as the road expands.

Glass containers may crack when hot liquid is placed in them. This is because the inner surface of the glass expands rapidly, before the heat has conducted through to the outer surface. The force of expansion cracks the glass. To overcome this, glass such as Pyrex has been developed that expands very little on heating. An alternative is toughened glass, which has been treated with chemicals to reduce the chance of cracking.

Figure 10.12 This truck is about to cross an expansion joint on a motorway bridge. On a hot day, the bridge expands and the interlocking 'teeth' of the joint move closer together.

The expansion of gases

Gases expand when they are heated, just like solids and liquids. We can understand this using the kinetic model of matter (see Chapter **9**). Figure **10.13** shows some gas in a cylinder fitted with a piston. At first, the gas is cold and its particles press weakly on the piston. When the gas is heated, its particles move faster. Now they push with greater force on the piston and push it upwards. The gas has expanded.

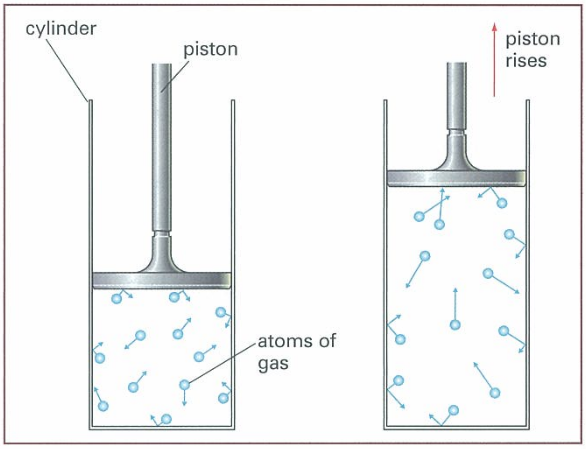


Figure 10.13 A gas expands when it is heated at constant pressure.

The upward force of the gas is balanced by the downward weight of the piston. So, in this situation, the pressure of the gas has remained constant as it has expanded. If the piston did not move, the **volume** of the gas would remain constant when it was heated but its **pressure** would increase.

Activity 10.3 Observing expansion

Try out some experiments to observe the expansion of solids, liquids and gases.

E

Comparing solids, liquids and gases

Solids, liquids and gases – which expands most for a given rise in temperature?

- Solids expand most slowly when they are heated. Some, such as Pyrex glass and invar metal, have been designed to expand as little as possible.
- Liquids generally expand faster than solids.
- Gases expand faster still.

There are some exceptions to this. For example, liquid paraffin expands very rapidly on heating. Petrol (gasoline) also expands rapidly when it is heated. If, on a hot day, a motorist fills up with petrol from cool underground tanks, the fuel may expand and overflow as it warms up.

QUESTIONS

6 Explain how Galileo's thermometer (see Figure **10.4**) makes use of thermal expansion.

7 Figure **10.14** shows an experiment to demonstrate the expansion of water.
  a Describe and explain what will happen when the flask of cold water is placed in the tank of hot water.
  b How could this experiment be adapted to compare the rates of expansion of water and of liquid paraffin?

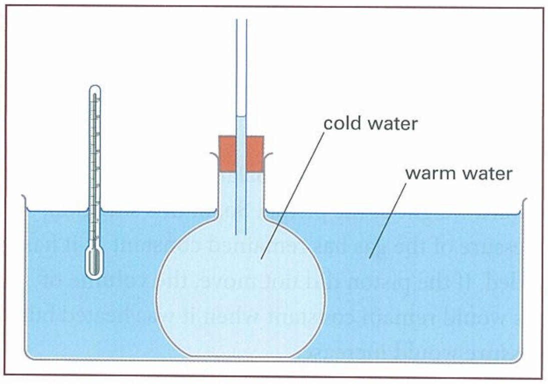


Figure 10.14 Demonstrating the thermal expansion of water – for Question **7**.

10.3 Thermal capacity

Some houses are fitted with night storage heaters. These are electrical heaters that heat up at night, when electricity is cheap. Then, during the day, they remain warm and give out their heat to the room.

Figure **10.15** shows the construction of a night storage heater. The electric heating elements are surrounded by special bricks that store the energy supplied by the electricity. The bricks are made of a material that requires a lot of energy to heat it up. In this way, the bricks store a lot of energy in a small space.

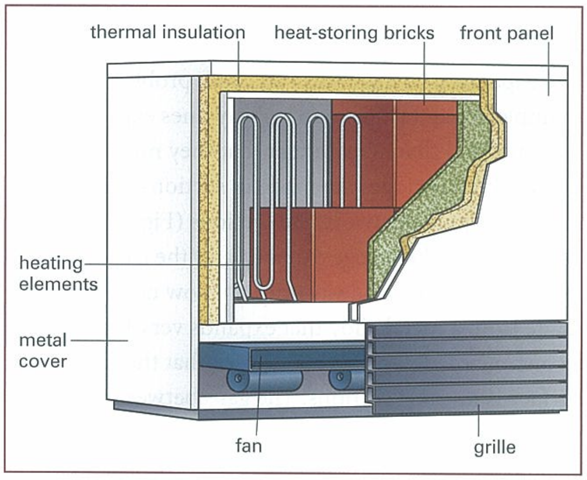


Figure 10.15 Inside a night storage heater. It is the bricks that store energy.

We say that the bricks have a high **thermal capacity**. It takes a lot of energy to raise their temperature by a certain amount. The bricks in a storage heater must be quite big if they are to have sufficient thermal capacity to keep a room warm for several hours. Because of their high thermal capacity, they heat up slowly and they cool down slowly.

The thermal capacity of an object depends on the material it is made of. Metal objects heat up easily – their thermal capacities are low. Objects made of non-metals (such as wood, glass and plastics) and liquids (such as water and oil) have higher thermal capacities.

QUESTIONS

8 A cook places a metal baking tray and a ceramic dish in the oven. She notices that the metal tray is soon too hot to touch while the ceramic dish takes longer to get hot. Which object has the greater thermal capacity? Explain your answer.

9 An electrical storage heater uses bricks to store energy. Explain why brick is a better choice of material than a metal such as steel.

E

10.4 Specific heat capacity

Suppose that you want to make a hot drink for yourself and some friends. You need to boil some water. You will be wasting energy if you put too much water in the kettle or pan. It is sensible to boil just the right amount. Also, if the water from your tap is really cold, it will take longer, and require more energy, to reach boiling point.

So the amount of energy you need to supply to boil the water will depend on two facts:

1 the mass of the water
2 the increase in temperature.

In order to calculate how much energy must be supplied to boil a certain mass of water, we need to know one other fact:

3 it takes 4200 J to raise the temperature of 1 kg of water by 1 °C.

Let us assume that the cold water from your tap is at 20 °C. You have to provide enough energy to heat it to 100 °C, so its temperature must increase by 80 °C. Let us also assume that you need 2 kg of water for all the drinks. The amount of energy required to heat 2 kg of water by 80 °C is therefore:

$$\text{energy required} = 2 \times 4200 \times 80$$
$$= 672\,000\,\text{J} = 672\,\text{kJ}$$

Another way to express the third fact above is to say that the specific heat capacity of water is 4 200 J per kg per °C or 4200 J/(kg °C).

E

In general, the **specific heat capacity (s.h.c.)** of any substance (not just water) is defined as follows:

> The specific heat capacity (s.h.c.) of a substance is the energy required to raise the temperature of 1 kg of the substance by 1 °C.

We can write the equation above as a general formula:

> energy required = mass × specific heat capacity × increase in temperature

Worked example 1 shows how to use this formula in more detail. There is more about the meaning of specific heat capacity (s.h.c.) after Worked example 1.

Worked example 1

A domestic hot water tank contains 200 kg of water at 20 °C. How much energy must be supplied to heat this water to 70 °C? (Specific heat capacity of water = 4200 J/(kg °C).)

Step 1: Calculate the required increase in temperature.

increase in temperature
= 70 °C − 20 °C = 50 °C

Step 2: Write down the other quantities needed to calculate the energy.

mass of water = 200 kg
specific heat capacity of water
= 4200 J/(kg °C)

Step 3: Write down the formula for energy required, substitute values, and calculate the result.

energy required = mass × specific heat capacity × increase in temperature
= 200 kg × 4200 J/(kg °C) × 50 °C
= 42 000 000 J
= 42 MJ

So 42 MJ are required to heat the water to 70 °C.

The meaning of s.h.c.

Energy is needed to raise the temperature of any material. The energy is needed to increase the kinetic energy of the particles of the material. In solids, they vibrate more. In gases, they move about faster. In liquids, it is a bit of both.

We can compare different materials by considering standard amounts (1 kg), and a standard increase in temperature (1 °C). Different materials require different amounts of energy to raise the temperature of 1 kg by 1 °C. In other words, they have different **specific heat capacities** (s.h.c.). Table **10.1** shows the values of s.h.c. for a variety of materials.

From the table, you can see that there is quite a wide range of values. The s.h.c. of steel, for example, is one-tenth that of water. This means that, if you supplied equal amounts of energy to 1 kg of steel and to 1 kg of water, the steel's temperature would rise ten times as much.

Type of material	Material	Specific heat capacity / J/(kg °C)
metals	steel	420
	aluminium	910
	copper	385
	gold	300
	lead	130
non-metals	glass	670
	nylon	1700
	polythene	2300
	ice	2100
liquids	water	4200
	sea water	3900
	ethanol	2500
	olive oil	1970
gases	air	1000
	water vapour	2020 (at 100 °C)
	methane	2200

Table 10.1 Specific heat capacities of a variety of materials.

The s.h.c. of water

Water is an unusual substance. As you can see from Table **10.1**, it has a high value of s.h.c. compared to other materials. This has important consequences:

- It takes a lot of energy to heat up water.
- Hot water takes a long time to cool down.

The consequences of this can be seen in our climates. In the hot months of summer, the land warms up quickly (low s.h.c.) while the sea warms up only slowly. In the winter, the sea cools gradually while the land cools rapidly. People who live a long way from the sea (in the continental interior of North America or Eurasia, for example) experience freezing winters and very hot summers. People who live on islands and in coastal areas (such as western Europe) are protected from climatic extremes because the sea acts as a reservoir of heat in the winter, and stays relatively cool in the summer.

Measuring s.h.c.

One method for measuring the specific heat capacity of a metal is shown in Figure **10.16a**. The block of aluminium has a mass of 1 kg. It is heated by a small electric heater, which supplies 50 J every second (its power is 50 W). The thermometer shows the temperature rise of the block.

One approach is to heat the block for a certain length of time, and find the temperature rise. Knowing the time and the power of the heater, you can work out how much energy has been supplied. Then, knowing the temperature rise and the mass of the block, you can calculate the s.h.c.

A better approach is to record the temperature every ten seconds or so, and then plot a graph (Figure **10.16b**) to show the rate at which it is rising. From the slope of the graph, you can then work out how much the temperature rises every second. This is the temperature rise produced by 50 J of energy, and now you can work out the s.h.c.

It is important to evaluate the procedure being used, to judge how accurate the final result is likely to be. The metal block should be insulated, to prevent energy escaping; but, some will still escape. Also, some energy

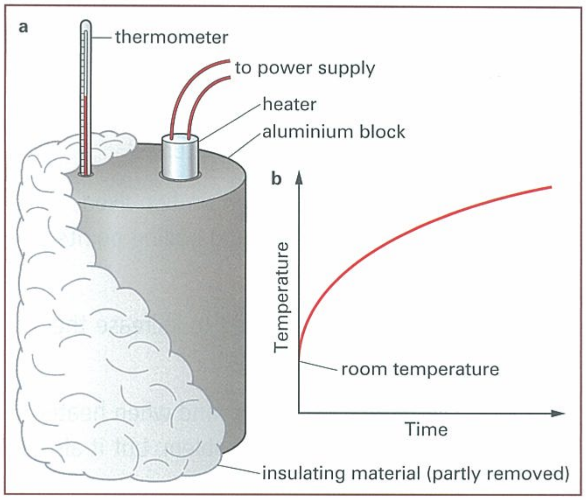


Figure 10.16 Measuring the specific heat capacity of aluminium. **a** The 1 kg aluminium block is heated by an electric heater, and its temperature is recorded at regular intervals. The block is covered in insulating material during the experiment, to reduce heat losses. A small amount of oil fills the gap between the thermometer and the block, ensuring that there is good thermal contact between them. The thermometer then gives reliable readings of the block's temperature. **b** This graph shows how the block's temperature increases. As the temperature rises, more heat escapes to the surroundings and the temperature rises more slowly.

is used in heating the heater itself, rather than the block. Both factors mean that the energy supplied is greater than the energy that heats the block, so the final answer will be too big. Another problem is that the block must not be heated too quickly. It takes time for the heat to conduct through the metal. It is desirable for the whole block to heat up at the same time, otherwise the thermometer will only indicate the temperature of part of the block.

Activity 10.4 Measuring s.h.c.

Measure the specific heat capacity of a metal in the form of a block.

QUESTIONS

10 The specific heat capacity of steel is 420 J/(kg °C).
  a How much energy is required to heat 1 kg of steel by 20 °C?
  b How much energy is required to heat 5 kg of steel by 20 °C?

11 A beaker contains 1 kg of water at 20 °C. A student heats a 1 kg block of aluminium to 100 °C and then drops it into the water. After a short while, the water and the block have both reached a temperature of 38 °C. The student said that this showed that water has a greater specific heat capacity than aluminium. Was he correct? Explain your answer.

12 A thermocouple can be used as a thermometer. Such a thermometer can measure rapidly varying temperatures because of its small thermal capacity.
  a Explain why a thermocouple has a small thermal capacity.
  b Explain why this makes it suitable for measuring rapidly varying temperatures.

10.5 Latent heat

Energy must be supplied to a substance to melt it or to boil it – in other words, to make it change state. This energy does not increase the substance's temperature, and for this reason it is known as **latent heat** (the word 'latent' means 'hidden').

The energy needed to change a liquid into a gas is called the **latent heat of vaporisation**. The energy needed to change a solid into a liquid is called the **latent heat of fusion**. (Here, the word 'fusion' means 'melting'.) To compare different substances fairly, we measure the energy required to change the state of 1 kg of the substances. (Here, as for s.h.c., we use the word 'specific' to mean that it relates to unit mass, that is, 1 kg.). So **specific latent heat** is defined as follows:

> The specific latent heat of vaporisation is the energy required to cause 1 kg of a substance to change state from liquid to gas at its boiling point.
>
> The specific latent heat of fusion is the energy required to cause 1 kg of a substance to change state from solid to liquid at its melting point.

As we saw in section **9.3**, this energy is needed to break the bonds between particles.

E

Measuring latent heat

To determine the specific latent heat of a substance, 1 kg of the substance must be heated at its melting or boiling point until it entirely changes state. The amount of energy supplied must be measured. Then we have:

$$\text{specific latent heat} = \frac{\text{energy supplied}}{\text{mass}}$$

To measure the specific latent heat of fusion of ice, a measured mass of ice at 0 °C is added to warm water in a well-insulated copper container. When the ice has entirely melted, the temperature of the water is measured. Knowing the specific heat capacities of water and copper, the energy they have lost to the ice can be calculated. This is the latent heat, and the energy per kilogram can be calculated.

Similarly, water can be boiled using an electric heater of known power. The mass of water that boils away is measured, and the energy supplied by the heater is calculated.

QUESTIONS

13 Explain why the definition of specific latent heat of fusion includes the phrase '… at its melting point'.

14 It takes 4500 J to turn 2.0 g of water at 100 °C into steam. Calculate the specific latent heat of vaporisation of water.

15 Use the kinetic (particle) model of matter to explain why the specific latent heat of vaporisation of water is much greater than the specific latent heat of fusion of ice.

Summary

Thermometers are used to measure temperature. Any thermometer makes use of a physical property that varies with temperature.

Any temperature scale is based on two fixed points, such as the freezing and boiling points of pure water.

E

Thermometers can be designed to increase their sensitivity, range and linearity.

Solids, liquids and gases all expand when heated. Thermal expansion can be a problem, but it also has many uses.

E

In general, gases expand more than liquids, which expand more than solids.

It takes a lot of energy to raise the temperature of an object with a high thermal capacity.

E

The specific heat capacity of a substance is the energy required to raise the temperature of 1 kg of the substance by 1 °C.

The specific latent heat of vaporisation is the energy required to cause 1 kg of a substance to change state from liquid to gas at its boiling point.

The specific latent heat of fusion is the energy required to cause 1 kg of a substance to change state from solid to liquid at its melting point.

End-of-chapter questions

10.1 A student is using a thermometer to measure temperatures in a laboratory. The thermometer contains mercury. As the temperature increases, the length of the mercury column in the thermometer increases.

a Explain why the mercury column becomes longer. [1]

b The thermometer measures temperatures on the Celsius scale. Table **10.2** gives details of the **two** fixed points of the scale. Copy and complete the table. [2]

	Definition	Value
lower fixed point	melting point of pure ice	……
upper fixed point	……	100 °C

Table 10.2 For Question **10.1b**.

c Give another property of a material that varies with temperature and may be used to measure temperature. [1]

10.2 A student heats an insulated steel block using an electrical heater. The temperature of the block rises.

a The heater supplies energy to the block. In what form does the block store this energy? [1]

b The student then heats a second block, made of copper. The heater supplies energy at the same rate as before. The temperature of this block rises faster than that of the steel block. Which block has the greater thermal capacity? Explain your answer. [2]

10.3 A student is investigating two thermometers. She notices that their scales are marked differently.

- Liquid-in-glass thermometer: scale from −10 °C to +110 °C.
- Thermocouple thermometer: scale from −200 °C to +450 °C.

a Which thermometer has the greater range? [1]

The student places both thermometers in pure, melting ice. Each shows that the temperature is 0 °C.

b State another temperature at which you would expect the two thermometers to give the same reading. Explain your answer. [2]

She then places the two thermometers in a beaker of warm water. The liquid-in-glass thermometer shows that the temperature is 45.5 °C. The thermocouple thermometer reads 43 °C.

c Which thermometer is more sensitive? Explain how you know. [2]

d Suggest why the two thermometers do not indicate the same temperature when they are placed in the beaker of water. [2]

10.4 Willem has to measure the specific heat capacity of copper. He has a copper block, which he heats with an electrical heater. The heater supplies energy to the block at a rate of 50 J each second.

Willem records the temperature of the block. Then he switches on the heater for exactly 10 minutes.

a What **two** other measurements will he require in order to calculate the specific heat capacity of steel? [2]

b Explain why the block must be well insulated if he is to obtain an accurate result. [1]

c If the block is poorly insulated, will Willem's result be too high or too low? [1]

11 Thermal (heat) energy transfers

Core	Demonstrating conduction, convection and radiation
E Extension	Explaining conduction
Core	Explaining convection and radiation
E Extension	Comparing good and bad emitters of radiation
Core	Discussing applications and consequences of thermal (heat) energy transfer

Warming up, keeping cool

Mammals are warm-blooded creatures. They keep their body temperature at about 35–40 °C. The reason for this is that mammals are active creatures. If they are carnivores, they may have to sprint suddenly to catch their prey. Herbivores may have to graze for most of the day, occasionally running to avoid the carnivores. Muscles work much better at higher temperatures because the reactions that release energy go faster. People are mammals. If you have camped out overnight, you may have experienced the difficulty of getting your muscles to start working when you wake up on a cold morning.

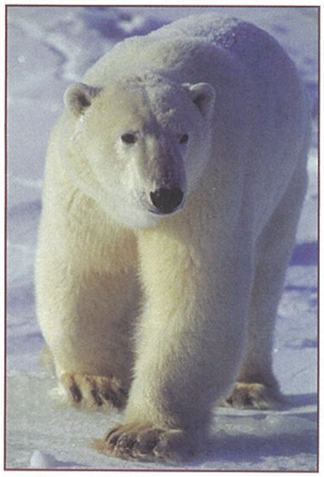
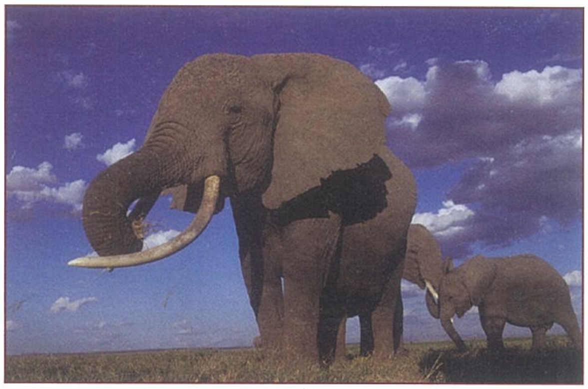


Figure 11.1 The polar bear has thick fur to help it retain heat. It is a very bulky animal, so that its surface area is small compared to its volume. This is another way of retaining heat.

There are problems with being warm-blooded. The polar bear (Figure **11.1**) lives in a very cold climate. It is in constant danger of freezing to death. To avoid this danger, polar bears have thick coats of waterproof fur, so that heat cannot easily escape. They are also very bulky. This means that they have a relatively small surface area, compared to their volume. They have a lot more 'inside' than 'outside', and so they find it easier to retain their body heat. Grizzly bears also live in cold areas, and they too are bulky. Bears that live closer to the equator, such as the European brown bear, tend to be much smaller. They do not have such problems with retaining heat.

African elephants (Figure **11.2**) have the opposite problem. They are large animals living in a hot climate, and they are in danger of over-heating if they are too active. To cool off, they use their ears. On a hot day, more blood flows through the veins in their ear flaps. This warms the air nearby, so that heat escapes by convection. Flapping the ears increases the rate of heat loss. An elephant's ear flaps are thus the equivalent of a car's radiator – a way of getting rid of excess heat. Wallowing in mud can also be cooling. As water evaporates from the elephant's skin, it carries energy away.



All creatures have ways of regulating their body temperatures. They make use of all the different ways in which heat moves around: conduction, convection, radiation and evaporation.

Figure 11.2 An African elephant has large ear flaps, but these are not to improve its hearing. They help it to get rid of excess heat on a hot day, or when they have been very active. Blood flow to the veins in the ears is increased. This warms the nearby air and the heat is carried away by convection.

11.1 Conduction

As we discussed in Chapter **6**, thermal (heat) energy is energy transferring from a hotter place to a colder place – in other words, from a higher temperature to a lower temperature. Thermal energy requires a **temperature difference** if it is to be transferred. In this chapter we look at the various ways in which thermal energy is transferred. We start with **conduction**.

Lying on the table are two spoons: one is metal, the other is plastic. You pick up the metal spoon – it feels cold. You pick up the plastic spoon – it feels warm. In fact, both are at the same temperature, room temperature, as a thermometer would prove to you. How can this be? What you are detecting is the fact that metals are good conductors of heat, and plastics are poor conductors of heat. Figure **11.3** shows what is going on.

a When your finger touches a metal object, heat is conducted out of your finger and into the metal. Because metal is a good **conductor**, heat spreads rapidly through the metal. Heat continues to escape from your finger, leaving it colder than before. The temperature-sensitive nerves in your finger tip tell your brain that your finger is cold. So you think you are touching something cold.

b When you touch a plastic object, heat conducts into the area that your finger is in direct contact with. However, because plastic is a good **insulator**, the heat travels no further. Your finger loses no more heat and remains warm. The message from the nerves in your finger tip is that your finger is warm. So you think you are touching something warm.

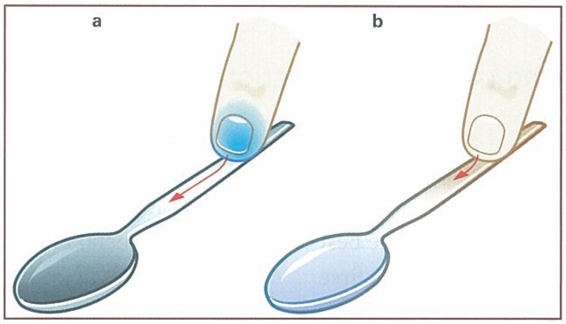


Figure 11.3 Metals feel cold, plastics feel warm. **a** Touching a piece of metal. Heat flows from your finger and into the metal. Because metals are good conductors of heat, heat continues to escape from your finger. Your finger gets colder. **b** Touching a piece of plastic. A small amount of heat conducts into the plastic. But it can go no further, because plastics are good insulators. Your finger stays warm.

(Note that the nerves in your finger tell you how hot your finger is, not how hot the object is that you are touching. This is similar to our discussion of thermometers in Chapter **10**. A thermometer in water indicates its own temperature, and we have to assume that the temperature of the water is the same as this.)

Table **11.1** compares conductors and insulators. You can see that, in general, metals are good conductors of heat while non-metals are poor conductors.

best conductor	diamond	*worst insulator*
	silver, copper	
	aluminium, steel	
	lead	
	ice, marble, glass	
	polythene, nylon	
	rubber, wood	
	polystyrene	
worst conductor	glass wool	*best insulator*

Table 11.1 Comparing conductors of heat, from the best conductors to the worst. A bad conductor is a good insulator. Almost all good conductors are metals; polymers (plastics) are at the bottom of the list. Glass wool is an excellent insulator because it is mostly air.

Demonstrating conduction

Figure **11.4** shows one way to compare different metals. The metals rods are all the same size. Each has a blob of wax at one end. They are all heated equally at the other end. The best conductor is the metal on which the wax melts first.

Figure **11.5** shows how to demonstrate that water is a poor conductor of heat. A lump of ice is trapped at the bottom of the test tube, held in place by a piece of wire gauze. The water is heated close to the mouth of the tube. The water boils, while the ice remains frozen. Heat has not conducted down to the bottom of the tube. The water there remains cold and the ice does not melt.

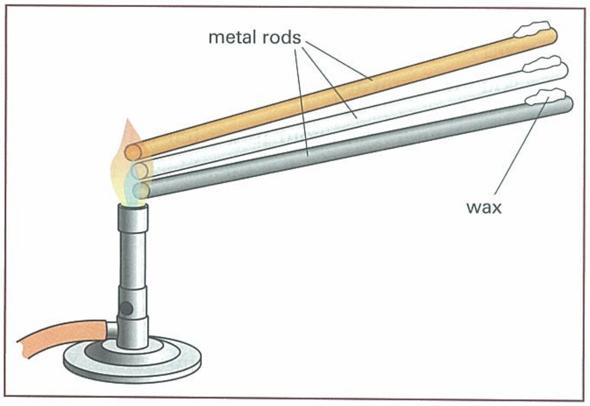


Figure 11.4 An experiment to show which metal is the best conductor of heat.

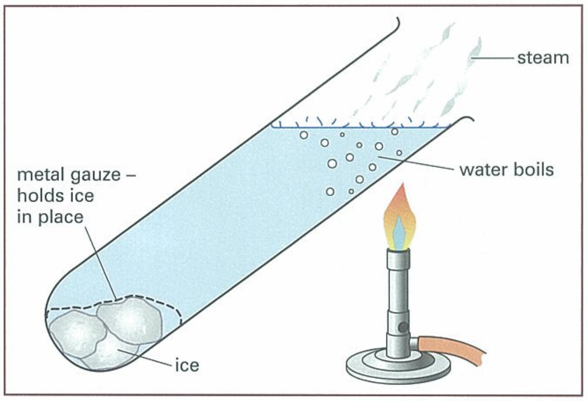


Figure 11.5 Although the water at the top of the tube is boiling, the ice at the bottom remains solid.

Activity 11.1 Investigating conduction

Try out some experiments that involve conduction of heat.

QUESTIONS

1 a Name a good conductor of heat (a thermal conductor).
  b Name a good thermal insulator.
2 What is needed for heat to flow through a conductor?
3 Look at Table **11.1**. Which will feel colder to the touch, marble or polystyrene?

E

Explaining conduction in metals and non-metals

Both metals and non-metals conduct heat. Metals are generally much better conductors than non-metals. We need different explanations of conduction for these two types of material.

We will start with **non-metals**. Imagine a long glass rod (Figure **11.6a**). One end is being heated, the other is cold. There is thus a temperature difference between the two ends, and heat flows down the rod. What is going on inside the rod?

E

We will picture the atoms that make up the glass as shown in Figure **11.6b**. (They are shown as being identical, and regularly arranged, although they are not really like this.) At the hot end of the rod, the atoms are vibrating a lot. At the cold end, they are vibrating much less. As they vibrate, the atoms jostle their neighbours. This process results in each atom sharing its energy with its neighbouring atoms. Atoms with a lot of energy end up with less, those with a little end up with more. The jostling gradually transfers energy from the atoms at the hot end to those at the cold end. Energy is steadily transferred down the rod, from hot to cold.

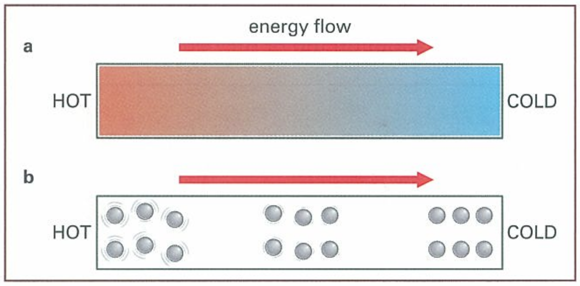


Figure 11.6 Conduction of heat in non-metals. **a** A glass rod, heated at one end and cooled at the other. Heat travels from the hot end to the cold end. **b** Energy is transferred because the vibrating atoms jostle one another. This shares energy between neighbouring atoms. The result is a flow of energy from the hot end to the cold end.

This is the mechanism by which poor conductors (such as glass, ice and plastic) conduct heat. It is also the mechanism in diamond, where the carbon atoms are tightly bonded to their neighbours. Any slight vibration of one atom is rapidly shared with its neighbours, and soon spreads through the whole piece of material.

However, **metals** are good conductors for another reason. In a metal there are particles called electrons that can move about freely. Electrons are smaller than atoms, and they are the particles that carry energy when an electric current flows through a metal. They also carry energy when heat is transferred through a metal.

Finally, **liquids** can also conduct heat, because the particles of which they are made are in close contact with one another. However, convection (see section **11.2** below) is often more important than conduction in the transfer of heat through a liquid.

11.2 Convection

'Hot air rises.' This is a popular saying. It is one of the few ideas from physics that almost everyone who has studied a little science can remember. Figure **11.7** is a photograph made using a technique that shows up currents in the air. You can see hot air rising from the heater, from the computer, and even from the man.

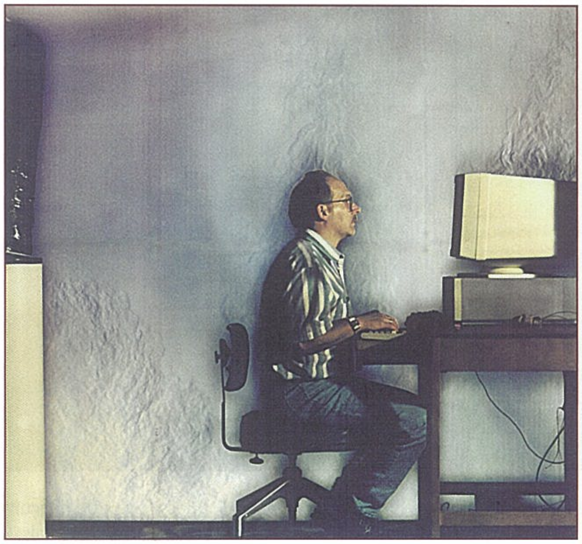


Figure 11.7 Warm air rises above any object that is warmer than its surroundings. In this office scene, there is a heater (lower left) that is producing warm air. Currents also rise above the computer and the operator.

When air is heated, its density decreases (it expands). Since it is less dense than its surroundings, it then floats upwards (just as a cork floats upwards if you hold it under water and then release it). Think about a hot air balloon. If it is to 'fly', the hot air in the balloon, plus the balloon fabric itself, plus the basket that hangs below, complete with occupants, must altogether have a density less than that of the surrounding colder air.

The rising of hot air is just one example of **convection**. Hot air can rise because air is a fluid, and convection is a phenomenon that can be observed in any fluid (liquid or gas).

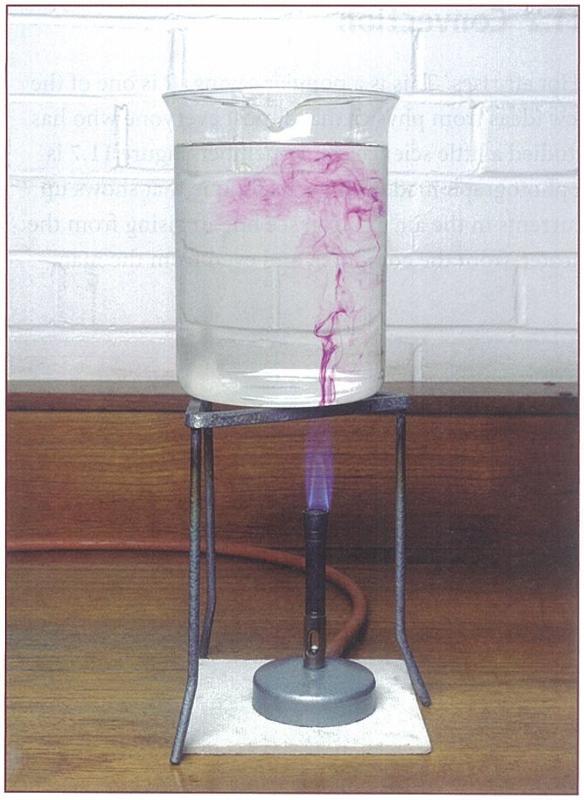


Figure 11.8 Because water is clear and colourless, it can be difficult to see how the water moves to form a convection current. Crystals of potassium manganate(VII) act as a purple dye to show up the movement of the water.

Demonstrating convection

Figure **11.8** shows how a convection current can be observed in water. Above the flame, water is heated and expands. Now its density is less than that of the surrounding water, and it floats upwards. The purple dye shows how it moves. Colder water, which is more dense, flows in to replace it.

A **convection current** is a movement of a fluid that carries energy from a warmer place to a cooler one. This highlights an important difference between convection and conduction.

- In convection, energy is transferred through a material from a warmer place to a cooler place by the movement of the material itself.
- In conduction, energy is transferred through a material from a warmer place to a cooler place without the material itself moving.

Convection currents at work

Convection currents help to share energy between warm and cold places. If you are sitting in a room with an electric heater, energy will be moving around the room from the heater as a result of convection currents, rising from the heater. You are likely to be the source of convection currents yourself, since your body is usually warmer than your surroundings (see Figure **11.9**). Many biting insects make use of this effect. For example, bed bugs crawl across the bedroom ceiling. They can detect a sleeping person below by finding the warmest spot on the ceiling. Then they drop straight down on the sleeper. This is a lot easier than crawling about on top of the bedding.

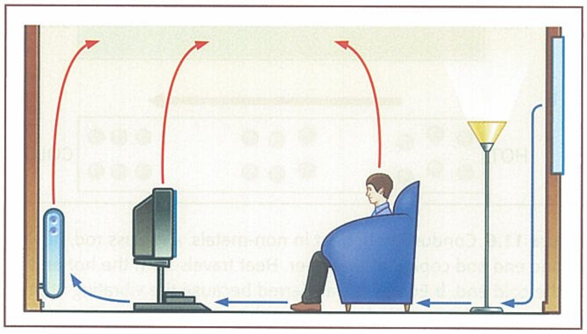


Figure 11.9 Convection currents rise above the warm objects in a room.

Cold objects also produce convection currents. You may have noticed cold water sinking below an ice cube in a drink. In a refrigerator, the freezing surface is usually positioned at the top and the back, so that cold air will sink to the bottom. Warm air rises to be re-chilled (see Figure **11.10**).

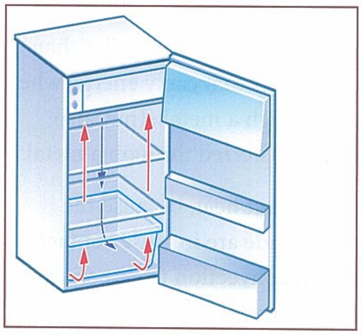


Figure 11.10 In a fridge, cold air sinks from the freezing compartment. If the freezer was at the bottom, cold air would remain there, and the items at the top would not be cooled.

Explaining convection

We have already seen that convection results from the **expansion** of a fluid when it is heated. Expansion means an increase in volume while mass stays constant – hence, density decreases. A less dense material is lighter, and is pushed upwards by the surrounding denser material.

The particles in the hotter fluid have more kinetic energy – they move around faster. As they flow from place to place, they take this energy with them.

Activity 11.2 Convection experiments

Try out some experiments that show convection at work.

QUESTIONS

4 'A thermal (heat) energy transfer by means of the motion of a fluid.' Is this a description of conduction or convection?

5 When a gas is heated, its particles gain energy. Imagine that you could see the particles of a hot gas and of a cold gas (at the same pressure).

  a What difference would you see in their movement?

  b What difference would you see in their separation?

6 What part does convection play in the spreading of energy around a room from an electric heater?

7 Write a brief explanation of convection, using the terms **expansion**, **density** and **gravity**.

8 Why would it not be a good idea to fit an electric heater near the ceiling in a room?

11.3 Radiation

At night, when it is dark, you can see much further than during the day. In the daytime, the most distant object you are likely to be able to see is the Sun, about 150 million kilometres away. At night, you can see much further, to the distant stars. The most distant object visible to the naked eye is the Andromeda galaxy, about 20 million million million kilometres away.

The light that reaches us from the Sun and other stars travels to us through space in the form of **electromagnetic radiation**. This radiation travels as electromagnetic waves. It travels over vast distances, following a straight line through empty space. As well as light, the Earth is bathed in other forms of electromagnetic radiation from the Sun, including infrared and ultraviolet.

The hotter an object, the more **infrared radiation** it gives out. You can use this idea to help you in doing a bit of detective work. Outside the house, a car is parked. How long has it been there? Hold your hands close to the engine compartment to see if you can detect heat radiating from it. Inside the house, the lights are out. Hold your hand close to the light bulb. Can you detect radiation, which will tell you that it was recently lit up?

Our skin detects the infrared radiation produced by a hot object. Nerve cells buried just below the surface respond to heat. You notice this if you are outdoors on a sunny day.

Here are the characteristics of infrared radiation that we have mentioned so far. Infrared radiation:

- is produced by warm or hot objects
- is a form of electromagnetic radiation
- travels through empty space (and through air) in the form of waves
- travels in straight lines
- warms the object that absorbs it
- is invisible to the naked eye
- can be detected by nerve cells in the skin.

Figure **11.11** shows another way of detecting infrared radiation, using a heat-sensitive camera. The photograph shows a boy sitting in front of a camera that detects infrared radiation. It is very sensitive to slight differences in temperature between different parts of the body.

Figure 11.11 Using an infrared-sensitive camera. Slight variations in body temperature show up as different colours. Cameras like this are used in medicine to detect skin disorders and infections.

QUESTIONS

9 How can energy be transferred through the vacuum of space: by conduction, by convection, or by radiation?

10 On Earth, we receive visible light from the Sun. Name **two** other forms of electromagnetic radiation that we receive from the Sun.

11 If an object's temperature is increased, what happens to the amount of infrared radiation it emits?

Good absorbers, good emitters

On a hot, sunny day, car drivers may park their cars with a sunshield behind the windscreen (Figure **11.12**). Such a sunscreen is usually white (or another light colour) or shiny, because this reflects away light and infrared radiation, which would make the car get uncomfortably hot. The black plastic parts of the car (such as the steering wheel and dashboard) are very good absorbers of infrared, and they can become too hot to touch.

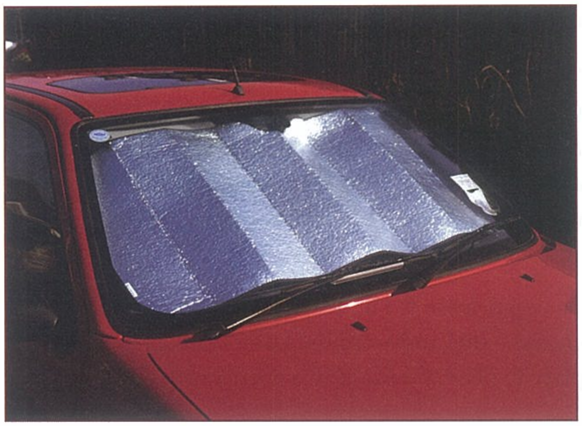


Figure 11.12 A sunscreen reflects away unwanted radiation, which would otherwise make the car unbearably hot.

It is the surface that determines whether an object absorbs or reflects infrared radiation (Figure **11.13**). A surface that is a good reflector is a poor absorber.

On a hot day, you may have noticed how the black surface of a tarred (metalled) road emits heat. Black surfaces readily absorb infrared radiation. They are also good emitters.

- Shiny or white surfaces are the best reflectors (the worst absorbers).
- Matt black surfaces are the best absorbers (the worst reflectors).
- Matt black surfaces are the best emitters.

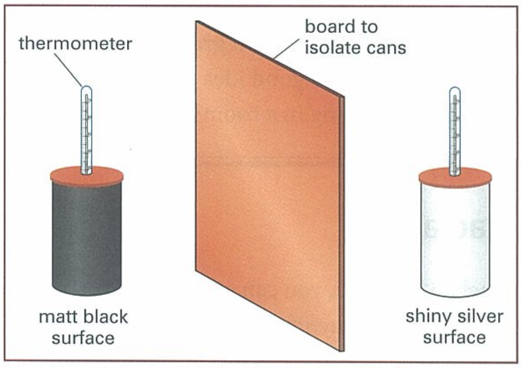


Figure 11.13 Which surface radiates better, black or shiny?

Figure **11.13** shows an experiment to compare the rates at which black and shiny surfaces emit radiation. One can has a matt black surface, and the other is shiny. Both are filled with hot water, and they cool by radiation. The black can cools more rapidly than the shiny one.

QUESTIONS

12 Suppose that you have a matt black surface and a shiny black surface.
  a Which is a better absorber of infrared radiation?
  b Which is a better emitter of infrared radiation?
  c Which is a better reflector of infrared radiation?

13 Look at Figure **11.13**. Use what you know about thermal (heat) energy transfers to explain why the cans must be fitted with lids, and why they should stand on a wooden or plastic surface.

Activity 11.3 Radiation experiments

Carry out some experiments (or watch demonstrations) showing how hot objects radiate.

11.4 Some consequences of thermal (heat) energy transfer

Hot objects have a lot of **internal energy**. As we have seen above, energy tends to escape from a hot object, spreading to its cooler surroundings by conduction, convection and radiation. This can be a great problem. We may use a lot of energy (and money) to heat our homes during cold weather, and the energy simply escapes. We eat food to supply the energy we need to keep our bodies warm, but energy escapes from us at a rate of roughly 100 watts (100 W = 100 J/s).

To keep energy in something that is hotter than its surroundings, we need to **insulate** it. Knowing about conduction, convection and radiation can help us to design effective insulation.

Home insulation

A well-insulated house can avoid a lot of energy wastage during cold weather. Insulation can also help to prevent the house from becoming uncomfortably hot during warm weather. Figure **11.14** shows some ways in which buildings can be insulated. More details of these are listed in Table **11.2**.

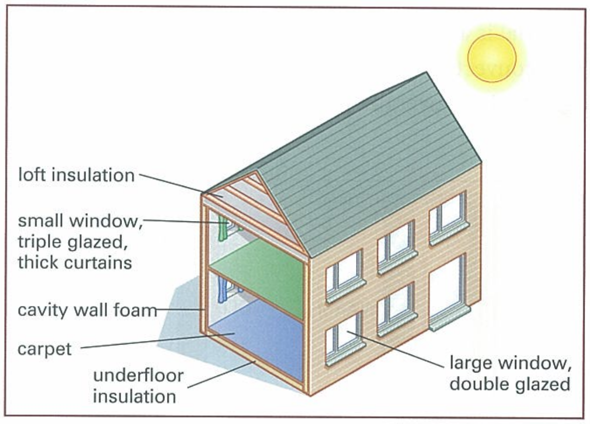


Figure 11.14 This house has been well designed to reduce the amount of fuel needed to keep it warm. The windows on the sunny side are large, so that the rooms benefit from direct radiation from the Sun. The windows on the other side are small, so that little energy escapes through them.

Method	Why it works
thick curtains, draught excluders	stops convection currents, and so prevents cold air from entering and warm air from leaving
loft and underfloor insulating materials	prevents conduction of heat through floors and ceilings
double and triple glazing of windows	vacuum between glass panes cuts out losses by conduction and convection
cavity walls	reduces heat losses by conduction
foam or rockwool in wall cavity	further reduces heat losses by convection

Table 11.2 Ways of retaining energy in a house

Double-glazed windows usually have a vacuum between the two panes of glass. This means that energy can only escape by radiation, since conduction and convection both require a material. Modern houses are often built with cavity walls, with an air gap between the two layers of bricks. It is impossible to have a vacuum in the cavity, and convection currents can transfer energy across the gap (see Figure **11.15a**). Filling the cavity with foam means that a small amount of energy is lost by conduction, although the foam material is a very poor conductor. However, this does stop convection currents from flowing (Figure **11.15b**), so there is an overall benefit.

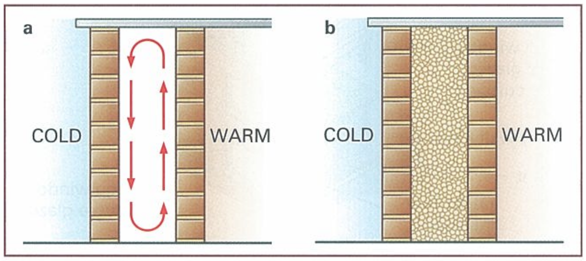


Figure 11.15 **a** A cavity wall reduces heat loss by conduction, because air is a good insulator. However, a convection current can transfer energy from the inner wall to the outer wall. **b** Filling the cavity with foam or mineral (glass or rock) wool prevents convection currents from forming.

Keeping cool

Vacuum (thermos) flasks are used to keep hot drinks hot. They can also be used to keep cold drinks cold. Giant vacuum flasks are used to store liquid nitrogen and helium at very low temperatures, ready for use in such applications as body scanners in hospitals.

Figure **11.16** shows the construction of a vacuum flask. Glass is generally used, because glass is a good insulator. However, some flasks are made of steel for added strength. The gap between the double walls is evacuated to reduce losses by conduction and convection. Silvering reduces losses by radiation by reflecting back any infrared radiation. A vital part is the stopper, which prevents losses by convection and evaporation.

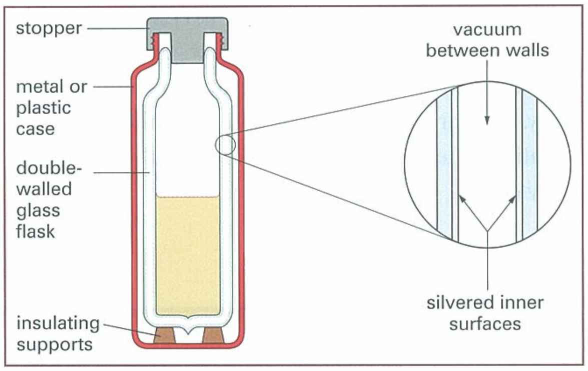


Figure 11.16 A vacuum flask is cleverly designed to keep hot things hot by reducing heat losses. It also keeps cold things cold. Although we might say 'it stops the cold getting out', it is more correct to say that it prevents heat from getting in. The first such flask was designed by James Dewar, a Scottish physicist, in the 1870s. He needed flasks to store liquefied air and other gases at temperatures as low as −200 °C. Soon after, people realised that a flask like this was also useful for taking hot or cold drinks on a picnic.

Convection, climate and weather

Convection currents explain the origins of winds and ocean currents, two of the major factors that control climate patterns around the world. For example, warm air rises above the equator, and colder air sinks in subtropical areas. This creates the pattern of Trade Winds that are experienced in the tropics.

Ocean currents (Figure **11.17**) help to spread warmth from equatorial regions to cooler parts of the Earth's surface. Warm water at the surface of the sea flows towards the poles. In polar regions, colder water sinks and flows back towards the equator. Provided this pattern remains constant, this helps to make temperate regions of the world more habitable. However, there is evidence that the pattern of ocean currents is changing, perhaps as a consequence of global warming.

QUESTIONS

14 List as many features as you can that contribute to the insulation of a house in a cold climate. For each, state whether it reduces heat loss by conduction, by convection or by radiation.

15 Why is it important to wear a hat on a very cold day?

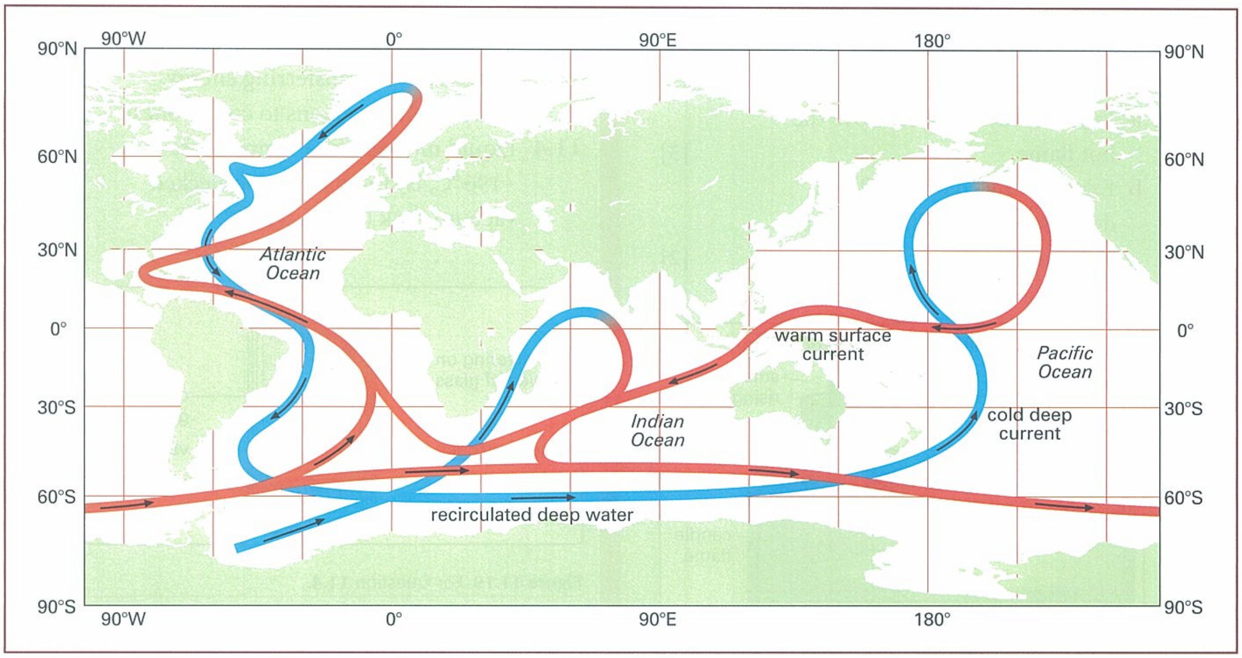


Figure 11.17 Ocean currents help to move energy from the tropics to cooler regions. Colder water from polar regions sinks and flows towards the equator. Warmer water flows closer to the ocean surface.

Summary

In general, metals are better conductors of heat than non-metals.

E Energy conducts through a solid when neighbouring particles collide and share energy, or when electrons transfer energy through the material.

Convection currents happen when a fluid expands and rises, because of its lower density.

Infrared radiation is part of the electromagnetic spectrum.

E Matt black surfaces are the best emitters and absorbers of radiation. Light, shiny surfaces are the best reflectors of radiation.

End-of-chapter questions

11.1 In cold climates, it is important to keep a house well insulated. Listed below are three ways of insulating a house. For each, explain how it reduces heat loss. In your answers, refer to conduction, convection or radiation, as appropriate.

- **a** Heavy curtains, when closed, trap air next to a window. [2]
- **b** Shiny metal foil is fitted in the loft, covering the inside of the roof. [2]
- **c** Glass wool is used to fill the gap in the cavity walls. [2]

11.2 Figure 11.18 shows a way of demonstrating a convection current in air.

a Explain why air rises above the hot flame. [3]

b Explain why colder air flows downwards through the other 'chimney'. [2]

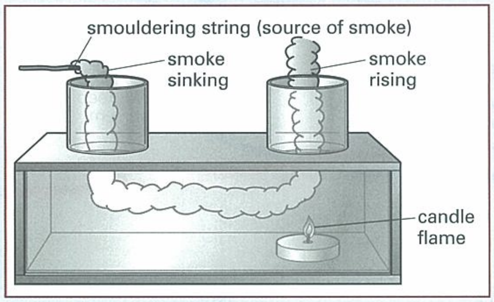


Figure 11.18 For Question 11.2.

E

11.3 a One end of a plastic rod is immersed in boiling water. The temperature of the other end gradually increases. Use ideas from the kinetic model of matter to explain how energy travels from one end of the rod to the other. [3]

b If the experiment was repeated using a metal rod of the same dimensions as the plastic rod, what difference would you expect to notice? [2]

E

c What particles in a metal are involved in transferring energy from hotter regions to colder ones? [1]

11.4 Liquid nitrogen, at a temperature of −196 °C, is stored in a wide-necked vacuum flask (Figure 11.19).

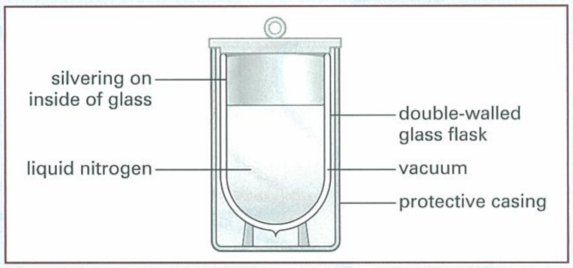


Figure 11.19 For Question 11.4.

a Explain the features of the design of this flask that help to keep the liquid nitrogen cold. [8]

b When **hot** drinks are stored in a vacuum flask, it is important to keep the stopper in the flask. Why is it less important to have a stopper in a flask that is being used to keep things **cold?** [2]