

CHAPTER 01 Heating processes

Due to increasing levels of carbon dioxide in the atmosphere, the Earth is getting warmer. The last two decades of the twentieth century were the warmest for over 400 years. In 2014, the Earth was the warmest since records began in 1890. These higher temperatures increase the severity of bushfires. The rate of evaporation from pastures also increases, drying the land and reducing the level of food production.

Thermal energy is part of our everyday experience. Humans can thrive in the climatic extremes of the Earth, from the outback deserts to ski slopes in winter.

Key knowledge

By the end of this chapter, you will have covered material from the study of the thermodynamic principles related to heating processes, including concepts of temperature, energy and work, and will be able to:

- convert temperature between degrees Celsius and kelvin
- describe the zeroth law of thermodynamics as two bodies in contact with each other coming to a thermal equilibrium
- describe temperature with reference to the average kinetic energy of the atoms and molecules within a system
- investigate and apply theoretically and practically the first law of thermodynamics to simple situations: $Q = U + W$
- explain internal energy as the energy associated with random disordered motion of molecules
- distinguish between conduction, convection and radiation with reference to heat transfer within and between systems
- investigate and analyse theoretically and practically the energy required to:
 - raise the temperature of a substance: $Q = mc\Delta T$
 - Change the state of a substance: $Q = mL$
- Explain why cooling results from evaporation using a simple kinetic energy model.

1.1 Heat and temperature

In the sixteenth century, Sir Francis Bacon, an English essayist and philosopher, proposed a radical idea: that heat is motion. He went on to write that heat is the rapid vibration of tiny particles within every substance. At the time, his ideas were dismissed because the nature of particles wasn't fully understood. An opposing theory at the time was that heat was related to the movement of a fluid called 'caloric' that filled the spaces within a substance.

Today, it is understood that all matter is made up of small particles (atoms or molecules). Using this knowledge, it is possible to look more closely at what happens during heating processes.

This section starts by looking at the kinetic particle model, which states that the small particles (atoms or molecules) that make up all matter have kinetic energy. This means that all particles are in constant motion, even in extremely cold solids. It was thought centuries ago that if a material was continually made cooler, there would be a point at which the particles would eventually stop moving. This coldest possible temperature is called **absolute zero** and will be discussed later in this section.

KINETIC PARTICLE MODEL

Some philosophers of the Middle Ages believed that heat was a fluid that filled the spaces between the particles of a substance and flowed from one substance to another. This is known as the 'caloric' theory. When caloric flowed from one substance into another, the first object cooled down and the second object heated up. Many attempts were made to detect caloric, but none were successful. It was assumed that caloric had no mass, odour, taste or colour. Scientists now know that caloric simply doesn't exist.

Much of our understanding of the behaviour of matter today depends on a model called the **kinetic particle model** (kinetic theory).

Recall that a model is a representation that describes or explains the workings within an object, system or idea.

These are the assumptions behind the kinetic particle model:

- All matter is made up of many very small particles (atoms or molecules).
- The particles are in constant motion.
- No kinetic energy is lost or gained overall during collisions between particles.
- There are forces of attraction and repulsion between the particles in a material.
- The distances between particles in a gas are large compared with the size of the particles.

The kinetic theory applies to all states (or phases) of matter: solids, liquids and gases.

Solids

Within a solid, the particles must be exerting attractive forces or bonds on each other for the matter to hold together in its fixed shape. There must also be repulsive forces, without which the attractive forces would cause the solid to collapse. In a solid, the attractive and repulsive forces hold these particles in more or less fixed positions, usually in a regular arrangement or lattice (see Figure 1.1.1(a)). But the particles in a solid are not completely still; they vibrate around average positions. The forces on individual particles are sometimes predominantly attractive and sometimes repulsive, depending on their exact position relative to neighbouring particles.

Liquids

Within a liquid, there is still a balance of attractive and repulsive forces. Compared with a solid, the particles in a liquid have more freedom to move around each other and will therefore take the shape of the container (see Figure 1.1.1(b)). Generally, the liquid takes up a slightly greater volume than it would in the solid state. Particles collide but remain attracted to each other, so the liquid remains within a fixed volume but with no fixed shape.

Gases

In a gas, particles are in constant, random motion, colliding with each other and the walls of the container. The particles move rapidly in every direction, quickly filling the volume of any container and occasionally colliding with each other (see Figure 1.1.1(c)). A gas has no fixed volume. The particle speeds are high enough that, when the particles collide, the attractive forces are not strong enough to keep the particles close together. The repulsive forces cause the particles to separate and move off in other directions.

PHYSICSFILE

States of matter: Plasma

The three basic phases (states) of matter are solid, liquid and gas. These are generally all that are discussed in secondary science.

There are in fact four phases of matter that are observable in everyday life—solid, liquid, gas and plasma. Under special conditions, several more exist. Plasma exists when matter is heated to very high temperatures and electrons are freed (ionisation). A gas that is ionised and has an equal number of positive and negative charges is called plasma. The interior of stars consists of plasma. In fact, most of the matter in the universe is plasma (Figure 1.1.2).



FIGURE 1.1.2 99.9 per cent of the visible universe is made up of plasma.

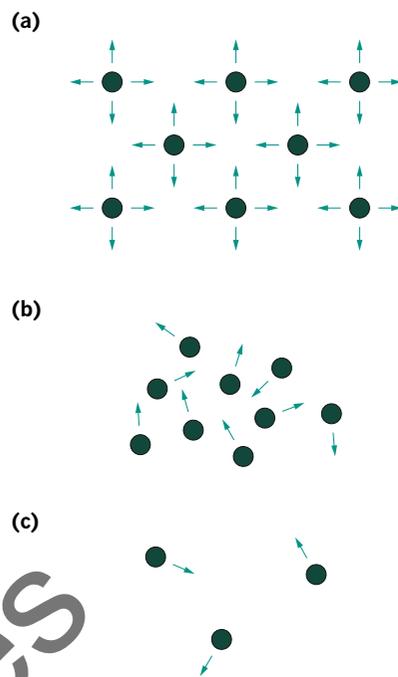


FIGURE 1.1.1 (a) Molecules in a solid have low kinetic energy and vibrate around average positions within a regular arrangement. (b) The particles in a liquid have more kinetic energy than those in a solid. They move more freely and will take the shape of the container. (c) Gas molecules are free to move in any direction.

THE KINETIC PARTICLE MODEL, INTERNAL ENERGY AND TEMPERATURE

The kinetic particle model can be used to explain the idea of heat as a transfer of energy. **Heat** (measured in joules) is the transfer of **thermal energy** from a hotter body to a colder one. Heating is observed by the change in **temperature**, the change of state or the expansion of a substance.

When a solid substance is 'heated', the particles within the material gain either **kinetic energy** (move faster) or **potential energy** (move away from their equilibrium positions).

The term heat refers to energy that is being transferred (moved). So it is incorrect to talk about heat contained in a substance. The term **internal energy** refers to the total kinetic and potential energy of the *particles within* a substance. Heating (the transfer of thermal energy) changes the internal energy of a substance by affecting the kinetic energy and/or potential energy of the particles within the substance. The movement of the particles in a substance due to kinetic energy is ordered: the particles move back and forth and we can model their behaviour. In comparison, the internal energy of a system is associated with the chaotic motion of the particles—it concerns the behaviour of a large number of particles that all have their own kinetic and potential energy.

PHYSICS IN ACTION

Energy

Energy is a very important concept in the study of the physical world, and is a focus in all areas of scientific study. Later chapters investigate energy in more detail.

Energy is a measure of an object's ability to do **work**. For example, raising an object's temperature or lifting an object is referred to as doing work. Work is measured in joules. The symbol for joules is J. Figure 1.1.3 shows the amount of joules available from some energy sources.

Kinetic energy is the energy of movement. It is equal to the amount of work needed to bring an object from rest to its present speed or to return it to rest. Potential energy is stored energy. There are many forms of potential energy, for example gravitational, nuclear, spring and chemical. Chemical potential energy is associated with the bonds between the particles of a substance. An increase in the potential energy of particles in a substance results in movement of the particles from their equilibrium positions.

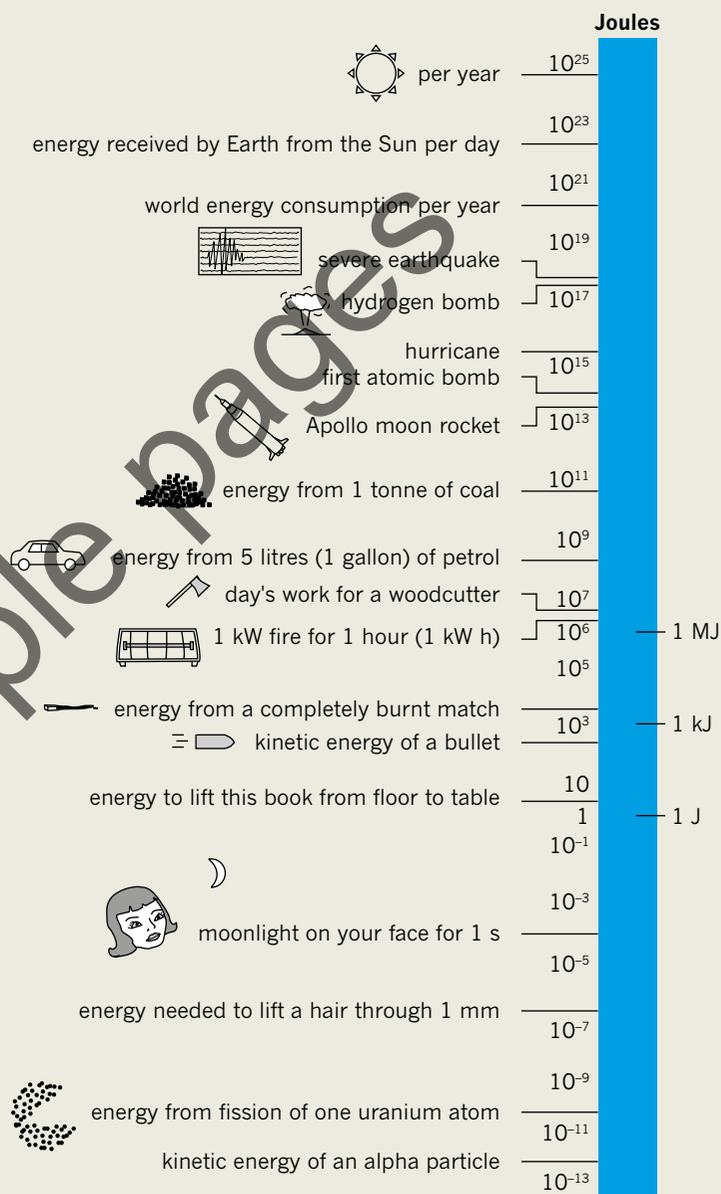


FIGURE 1.1.3 The comparative amounts of energy available from several sources.

- Heating is a process that always transfers thermal energy from a hotter substance to a colder substance.
- Heat is measured in joules (J).
- Temperature is related to the average kinetic energy of the particles in the substance. The faster the particles move, the higher the temperature of the substance.

Using the kinetic particle model, an increase in the total internal energy of the particles in a substance will result in an increase in temperature if there is a net gain in kinetic energy. Hot air balloons are an example of this process in action. The air in a hot air balloon is heated by a gas burner to a maximum of 120°C . The nitrogen (78%) and oxygen (21%) molecules in the hot air gain energy and so move a lot faster. The air in the balloon becomes less dense than the surrounding air, causing the balloon to float as seen in Figure 1.1.4.

Sometimes heating results only in the change of state or expansion of an object, and not a change in temperature. In these cases, the total internal energy of the particles has still increased but only the potential energy has increased, not the kinetic energy.

For instance, particles in a solid being heated will continue to be mostly held in place, due to the relatively strong interparticle forces. For the substance to change state from solid to liquid, it must receive enough energy to separate the particles from each other and disrupt the regular arrangement of the solid. During this 'phase change' process, the energy is used to overcome the strong interparticle forces, but not to change the overall speed of the particles. In this situation, the temperature does not change. This will be discussed in more detail in Section 1.3 'Latent heat'.

MEASURING TEMPERATURE

Only four centuries ago, there were no thermometers and people described heating effects by vague terms such as hot, cold and lukewarm. In about 1593, Italian inventor Galileo Galilei made one of the first thermometers. His 'thermoscope' was not particularly accurate as it did not take into account changes in air pressure, but it did suggest some basic principles for determining a suitable scale of measurement. His work suggested that there be two fixed points: the hottest day of summer and the coldest day of winter. A scale like this is referred to as an arbitrary scale, because the fixed points are randomly chosen.

Celsius and Fahrenheit scales

Two of the better known arbitrary temperature scales are the Fahrenheit and Celsius scales. Gabriel Fahrenheit of Germany invented the first mercury thermometer in 1714. While Fahrenheit is used in the United States of America to measure temperature, the system used in most of the countries of the world is the Celsius scale.

Absolute scales are different from arbitrary scales. For a scale to be regarded as 'absolute', it should have no negative values. The fixed points must be reproducible and have zero as the lowest value.

Kelvin scale

When developing the absolute temperature scale, the triple point of water provides one reliable fixed point. This is a point where the combination of temperature and air pressure allows all three states of water to coexist. For water, the triple point is only slightly above the standard freezing point (0.01°C) and provides a unique and repeatable temperature with which to adjust the Celsius scale.

The absolute or **kelvin** temperature scale is based on absolute zero and the triple point of water. See Figure 1.1.5 for a comparison of the kelvin and Celsius scales.

- i** • The freezing point of water (0°C) is equivalent to 273.15 K (kelvin). This is often approximated to 273 K.
- The size of each unit, 1°C or 1 K, is the same.
- The word 'degree' and the degree symbol are not used with the kelvin scale.
- To convert a temperature from degrees Celsius to kelvin: add 273.
- To convert a temperature from kelvin to degrees Celsius: subtract 273.

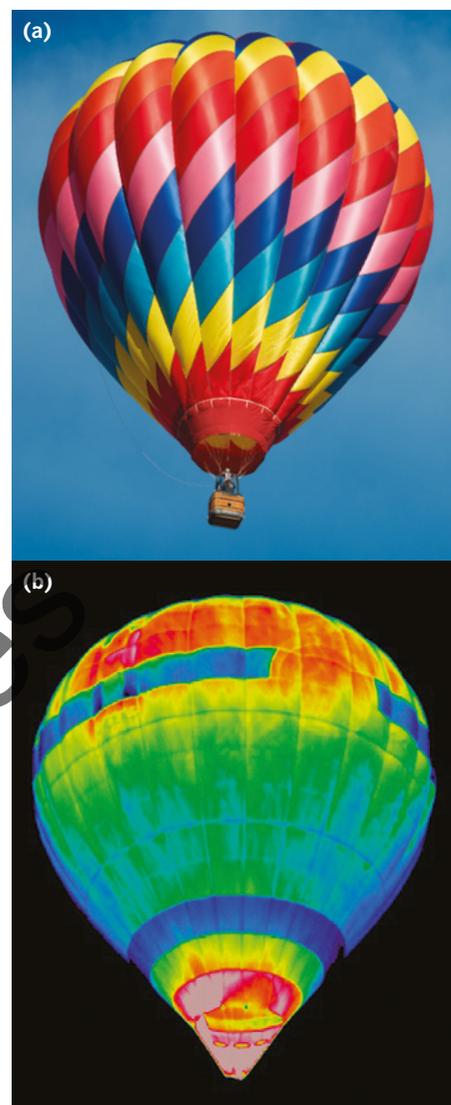


FIGURE 1.1.4 (a) Nitrogen and oxygen molecules gain energy when the air is heated, lowering the density of the air and causing the hot air balloon to rise off the ground. (b) A thermal image shows the temperature of the air inside the balloon.

- i** • 0°C is the freezing point of water at standard atmospheric pressure.
- 100°C is the boiling point of water at standard atmospheric pressure.

PHYSICSFILE

Unit conventions in physics

The unit for energy, the joule, is named after James Joule in recognition of his work. When a unit is named after a person, its symbol is usually a capital letter but the unit name is always lower case, e.g. joule (J), newton (N), kelvin (K).

Exceptions are degrees Celsius ($^{\circ}\text{C}$) and degrees Fahrenheit ($^{\circ}\text{F}$), which also include a degree symbol.

Units not named after people usually have both the symbol and the name in lowercase, e.g. metre (m), second (s).

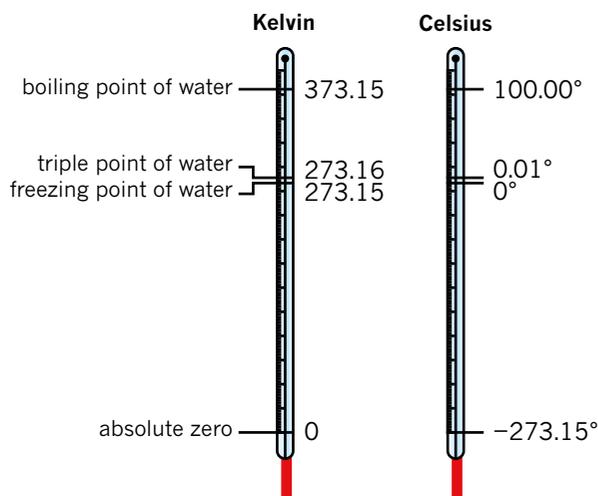


FIGURE 1.1.5 Comparison of the kelvin and Celsius scales. Note that there are no negative values on the kelvin scale.

- i** Absolute zero = $0\text{ K} = -273.15^{\circ}\text{C}$
- All molecular motion ceases at absolute zero. This is the coldest temperature possible.

Absolute zero

Experiments indicate that there is a limit to how cold things can get. The kinetic theory suggests that if a given quantity of gas is cooled, its volume decreases. The volume can be plotted against temperature and results in a straight line graph as shown in Figure 1.1.6.

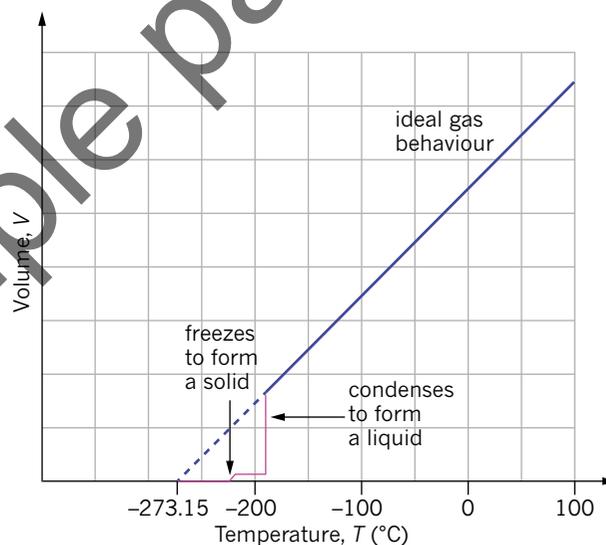


FIGURE 1.1.6 Gases have smaller volumes as they cool. This relationship is linear. Extrapolating (extending) the line to where the volume is zero gives a theoretical value of absolute zero.

PHYSICSFILE

Close to absolute zero

As temperatures get close to absolute zero, atoms start to behave in weird ways. Since the French physicist Guillaume Amontons first proposed the idea of an absolute lowest temperature in 1699, physicists have theorised about the effects of such a temperature and how it could be achieved. The laws of physics dictate that absolute zero itself can be approached but not reached. In 2003, researchers from NASA and MIT, in the United States of America, succeeded in cooling sodium atoms to one billionth of a degree above absolute zero. At this temperature, all elementary particles merge into a single state, losing their separate properties and behaving as a single 'super atom', a state first proposed by Einstein 70 years earlier.

THE LAWS OF THERMODYNAMICS

The topic of thermal physics involves the phenomena associated with the energy transfer between objects at different temperatures. Since the nineteenth century, scientists have developed four laws for this subject. The first two will be studied in this section.

The first, second and third laws had been known and understood for some time. Then another law was also determined. This final law was considered to be so important that it was decided to place it first, and so it is called the zeroth law of thermodynamics.

The zeroth law of thermodynamics

The zeroth law of thermodynamics relates to **thermal equilibrium** and **thermal contact** and allows temperature to be defined.

If two objects are in thermal contact, energy can flow between them. For example, if an ice cube is placed in a copper pan, the ice molecules are in thermal contact with the copper atoms. Assuming that the copper is warmer than the ice, thermal energy will flow from the copper to the ice.

Thermal equilibrium is when two objects in thermal contact stop having a flow of energy between them. If a frozen piece of steak is placed in a container of warm water, energy is transferred from the water to the steak. The steak gains energy and warms up. The water loses energy and cools down. Eventually the transfer of energy between the steak and water will stop. This point is called thermal equilibrium, and the steak and water will be at the same temperature.

i If objects A and B are each in thermal equilibrium with object C, then objects A and B are in thermal equilibrium with each other.

Two objects in thermal equilibrium with each other must be at the same temperature.

The first law of thermodynamics

The first law of thermodynamics states that energy simply changes from one form to another and the total internal energy in a system is constant. The internal energy of the system can be changed by heating or cooling, or by work being done on or by the system.

i Any change in the internal energy (ΔU) of a system is equal to the energy added by heating ($+Q$) or removed by cooling ($-Q$), minus the work done on ($-W$) or by ($+W$) the system.

$$\Delta U = Q - W$$

The internal energy (U) of a system is defined as the total kinetic and potential energy of the system. As the average kinetic energy of a system is related to its temperature and the potential energy of the system is related to the state, then a change in the internal energy of a system means that either the temperature changes or the state changes.

If heat (Q) is added to the system, then the internal energy (U) rises by either increasing temperature or changing state from solid to liquid or liquid to gas. Similarly, if work (W) is done on a system, then the internal energy rises and the system will once again increase in temperature or will change state by melting or boiling. When heat is added to a system or work is done on a system, ΔU is positive.

If heat (Q) is removed from the system, then the internal energy (U) decreases by either decreasing temperature or changing state from liquid to solid or gas to liquid. Similarly, if work (W) is done by the system, then the internal energy decreases and the system will once again decrease in temperature or change state by condensing or solidifying. When heat is removed from a system or work is done by a system, ΔU is negative.

If heat is added to the system and work is done by the system, then whether the internal energy increases or decreases will depend on the magnitude of the energy into the system compared to the magnitude of the energy out of the system.

Worked example 1.1.1

CALCULATING THE CHANGE IN INTERNAL ENERGY

A 1 L beaker of water has 25 kJ of work done on it and also loses 30 kJ of thermal energy to the surroundings. What is the change in energy of the water?

Thinking	Working
Heat is removed from the system, so Q is negative. Work is done on the system, so W is negative.	$\Delta U = Q - W$ $= -30 - (-25)$
Note that the units are kJ, so express the final answer in kJ.	$\Delta U = -5 \text{ kJ}$

Worked example: Try yourself 1.1.1

CALCULATING THE CHANGE IN INTERNAL ENERGY

A student places a heating element and a paddle-wheel apparatus in an insulated container of water. She calculates that the heater transfers 2530 J of thermal energy to the water and the paddle does 240 J of work on the water. Calculate the change in internal energy of the water.

1.1 Review

SUMMARY

- The kinetic particle theory proposes that all matter is made of atoms or molecules (particles) that are in constant motion.
- In solids, the attractive and repulsive forces hold the particles in more or less fixed positions, usually in a regular arrangement or lattice. These particles are not completely still—they vibrate about average positions.
- In liquids, there is still a balance of attractive and repulsive forces between particles but the particles have more freedom to move around. Liquids maintain a fixed volume.
- In gases, the particle speeds are high enough that, when particles collide, the attractive forces are not strong enough to keep them close together. The repulsive forces cause the particles to move off in other directions.
- Internal energy refers to the total kinetic and potential energy of the particles within a substance.
- Temperature is related to the average kinetic energy of the particles in a substance.
- Heating is a process that always transfers thermal energy from a hotter substance to a colder substance.
- Temperatures can be measured in degrees Celsius ($^{\circ}\text{C}$) or kelvin (K).
- Absolute zero is called simply 'zero kelvin' (0 K) and it is equal to -273.15°C .
- The size of each unit, 1°C or 1 K, is the same.
- To convert from Celsius to kelvin: add 273; to convert from kelvin to Celsius: subtract 273.
- The zeroth law of thermodynamics states that if objects A and B are each in thermal equilibrium with object C, then objects A and B are in thermal equilibrium with each other. A, B and C must be at the same temperature.
- The first law of thermodynamics states that energy simply changes from one form to another and the total energy in a system is constant.
- Any change in the internal energy (ΔU) of a system is equal to the energy added by heating ($+Q$) or removed by cooling ($-Q$), minus the work done on ($-W$) or by ($+W$) the system: $\Delta U = Q - W$.

1.1 Review *continued*

KEY QUESTIONS

- Which of the following is true of a solid?
 - Particles are moving around freely.
 - Particles are not moving.
 - Particles are vibrating in constant motion.
 - A solid is not made up of particles.
- An uncooked chicken is placed into an oven that has been preheated to 180°C . Which of the following statements describe what happens as soon as the chicken is placed in the oven? (More than one answer is possible.)
 - Thermal energy flows from the chicken into the hot air.
 - The chicken and the air in the oven are in thermal equilibrium.
 - Thermal energy flows from the hot air into the chicken.
 - The chicken and the air in the oven are not in thermal equilibrium.
 - A chicken is inside an oven that has been preheated to 180°C . The chicken has been cooking for one hour and its temperature is also 180°C . Which of the following statements best describes this scenario?
 - Thermal energy flows from the chicken into the hot air.
 - The chicken and the air in the oven are in thermal equilibrium.
 - Thermal energy flows from the hot air into the chicken.
 - The chicken and the air in the oven are not in thermal equilibrium.
- Which of the following temperature(s) cannot possibly exist? (More than one answer is possible.)
 - $1\,000\,000^{\circ}\text{C}$
 - -50°C
 - -50 K
 - -300°C
- A tank of pure helium is cooled to its freezing point of -272.2°C . Describe the energy of the helium particles at this temperature.
- Covert the following temperatures:
 - 30°C into kelvin
 - 375 K into degrees Celsius.
- Tank A is filled with hydrogen gas at 0°C and another tank, B, is filled with hydrogen gas at 300 K . Describe the difference in the average kinetic energy of the hydrogen particles in each tank.
- Sort the following temperatures from coldest to hottest:
freezing point of water
 100 K
absolute zero
 -180°C
 10 K
- A hot block of iron does 50 kJ of work on a cold floor. The block of iron also transfers 20 kJ of heat energy to the air. Calculate the change in energy (in kJ) of the iron block.
- A chef vigorously stirs a pot of cold water and does 150 J of work on the water. The water also gains 75 J of thermal energy from the surroundings. Calculate the change in energy of the water.
- A scientist very carefully does mechanical work on a container of liquid sodium. The liquid sodium loses 300 J of energy to its surroundings but gains 250 J of energy overall. How much work did the scientist do?

1.2 Specific heat capacity

A small amount of water in a kettle will experience a greater change in temperature than a larger volume if heated for the same time. A metal object left in the sunshine gets hotter faster than a wooden object. Large heaters warm rooms faster than small ones.

These simple observations suggest that the mass, material and the amount of energy transferred influence any change of temperature.

CHANGING TEMPERATURE

The temperature of a substance is a measure of the average kinetic energy of the particles inside the substance. To increase the temperature of the substance, the kinetic energy of its particles must increase. This happens when heat is transferred to that substance. The amount the temperature increases depends on a number of factors.

The greater the mass of a substance, the greater the energy required to change the kinetic energy of all the particles. So, the heat required to raise the temperature by a given amount is proportional to the mass of the substance.

$$\Delta Q \propto m$$

where ΔQ is the heat energy transferred in joules (J)

m is the mass of material being heated in kilograms (kg).

The more heat that is transferred to a substance, the more the temperature of that substance increases. The amount of energy transferred is therefore proportional to the change in temperature.

$$\Delta Q \propto \Delta T$$

where ΔT is the change in temperature in °C or K.

Heating experiments using different materials will confirm that these relationships hold true regardless of the material being heated. However, heating the same masses of different materials will show that the amount of energy required to heat a given mass of a material through a particular temperature change also depends on the nature of the material being heated. For example, a volume of water requires more energy to change its temperature by a given amount compared with the same volume of methylated spirits. For some materials, temperature change occurs more easily than for others.

i The **specific heat capacity** of a material, c , is the amount of energy that must be transferred to change the temperature of 1 kg of the material by 1°C or 1 K.

Combining these observations, the amount of energy added to or removed from the substance is proportional to the change in its temperature, its mass and its specific heat capacity (provided a material does not change state). The **specific heat capacity** of a material changes when the material changes state.

i As an equation:

$$Q = mc\Delta T$$

where Q is the heat energy transferred in joules (J)

m is the mass in kilograms (kg)

ΔT is the change in temperature in °C or K

c is the specific heat capacity of the material (J kg⁻¹ K⁻¹).

Material	c (J kg ⁻¹ K ⁻¹)
human body	3500
methylated spirits	2500
air	1000
aluminium	900
glass	840
iron	440
copper	390
brass	370
lead	130
mercury	140
ice (water)	2100
liquid water	4200
steam (water)	2000

TABLE 1.2.1 Approximate specific heat capacities of common substances.

Table 1.2.1 lists the specific heat capacities for some common materials. You can see that it also lists the average value for the human body, which takes into account the various materials within the body and the percentage that each material contributes to the body's total mass.

Worked example 1.2.1

CALCULATIONS USING SPECIFIC HEAT CAPACITY

A hot water tank contains 135 L of water. Initially the water is at 20°C. Calculate the amount of energy that must be transferred to the water to raise the temperature to 70°C.	
Thinking	Working
Calculate the mass of water. 1 L of water = 1 kg	Volume = 135 L so mass of water = 135 kg
ΔT = final temperature – initial temperature	$\Delta T = 70 - 20 = 50^\circ\text{C}$
From the table of specific heat capacities on page 10, $c_{\text{water}} = 4200 \text{ J kg}^{-1} \text{ K}^{-1}$. Use the equation $Q = mc\Delta T$.	$Q = mc\Delta T$ $= 135 \times 4200 \times 50$ $= 28\,350\,000 \text{ J}$ $= 28 \text{ MJ}$

Worked example: Try yourself 1.2.1

CALCULATIONS USING SPECIFIC HEAT CAPACITY

A bath contains 75 L of water. Initially the water is at 50°C. Calculate the amount of energy that must be transferred from the water to cool the bath to 30°C.

Worked example 1.2.2

COMPARING SPECIFIC HEAT CAPACITIES

Different states of matter of the same substance have different specific heat capacities. What is the ratio of the specific heat capacity of liquid water to that of ice?	
Thinking	Working
See Table 1.2.1 for the specific heat capacities of water in different states.	$c_{\text{water}} = 4200 \text{ J kg}^{-1} \text{ K}^{-1}$ $c_{\text{ice}} = 2100 \text{ J kg}^{-1} \text{ K}^{-1}$
Divide the specific heat of water by the specific heat of ice.	Ratio = $\frac{c_{\text{water}}}{c_{\text{ice}}}$ $= \frac{4200}{2100}$
Note that ratios have no units since the unit of each quantity is the same and cancels out.	Ratio = 2

Worked example: Try yourself 1.2.2

COMPARING SPECIFIC HEAT CAPACITIES

What is the ratio of the specific heat capacity of liquid water to that of steam?

PHYSICSFILE

The mass of water

Since water is a familiar material, many of the examples in this section use it as the liquid being heated. One kilogram of pure water has a volume of 1 litre at 4°C.

PHYSICSFILE

Specific heat capacity of water

One of the notable values in the table of specific heat capacities is the high value for water. It is 10 times, or an order of magnitude, higher than those of most metals listed. The specific heat capacity of water is higher than those of most common materials. As a result, water makes a very useful cooling and heat storage agent, and is used in areas such as generator cooling towers and car-engine radiators.

Life on Earth also depends on the specific heat capacity of water. About 70% of the Earth's surface is covered by water, and these water bodies can absorb large quantities of thermal energy without great changes in temperature. Oceans both heat up and cool down more slowly than the land areas next to them. This helps to maintain a relatively stable range of temperatures for life on Earth.

Scientists are now monitoring the temperatures of the deep oceans in order to determine how the ability of oceans to store large amounts of energy may affect climate change.

1.2 Review

SUMMARY

- When heat is transferred to or from a system or object, the temperature change depends upon the amount of energy transferred, the mass of the material(s) and the specific heat capacity of the material(s):

$$Q = mc\Delta T$$

where Q is the heat energy transferred in joules (J)

m is the mass of material being heated in kilograms (kg)

ΔT is the change in temperature ($^{\circ}\text{C}$ or K)

c is the specific heat capacity of the material ($\text{J kg}^{-1} \text{K}^{-1}$).

- A substance will have different specific heat capacities at different states (solid, liquid, gas).

KEY QUESTIONS

- Equal masses of water and aluminium are heated through the same temperature range. Using the values of c from Table 1.2.1 on page 10, which material requires the most energy to achieve this result?
- Which has the most thermal energy: 10 kg of iron at 20°C or 10 kg of aluminium at 20°C ?
- 100 mL of water is heated to change its temperature from 15°C to 20°C . How much energy is transferred to the water to achieve this temperature change?
- 150 mL of water is heated from 10°C to 50°C . What amount of energy is required for this temperature change to occur?
- For a 1 kg block of aluminium, x J of energy are needed to raise the temperature by 10°C . How much energy, in J, is needed to raise the temperature by 20°C ?
- Equal amounts of energy are absorbed by equal masses of aluminium and water. What is the ratio of the temperature rise of the aluminium to that of water?
- Which one or more of the following statements about specific heat capacity is true?
 - All materials have the same specific heat capacity when in solid form.
 - The specific heat capacity of a liquid form of a material is different from that of the solid and gas forms.
 - Good conductors of heat generally have high specific heat capacities.
 - Specific heat capacity is independent of temperature.
- If 4.0 kJ of energy is required to raise the temperature of 1.0 kg of paraffin by 2.0°C , how much energy (in kJ) is required to raise the temperature of 5.0 kg of paraffin by 1.0°C ?
- A cup holds 250 mL of water at 20°C . 10.5 kJ of heat energy is transferred to the water. What temperature does the water reach after the heat is transferred?
- A block of iron is left to cool. After cooling for a short time, 13.2 kJ of energy has been transferred away from the block of iron and its temperature has decreased by 30°C . What is the mass of the block of iron?

1.3 Latent heat

If water is heated, its temperature will rise. If enough energy is transferred to the water, eventually the water will boil. The water changes state (from liquid to gas). The **latent heat** is the energy released or absorbed during a change of state. Latent means hidden or unseen. While a substance changes state, its temperature remains constant. The energy used in, say, melting ice into water is hidden in the sense that the temperature doesn't rise while the change of state is occurring.

ENERGY AND CHANGE OF STATE

Look at the heating curve for water shown in Figure 1.3.1. This graph shows how the temperature of water changes as energy is added at a constant rate. Although the rate at which the energy is added is constant, the increase in temperature is not always constant. There are sections of increasing temperature, and sections where the temperature remains unchanged (the horizontal sections) while the material changes state. Temperature remains constant during the change in state from ice to liquid water and again from liquid water to steam.

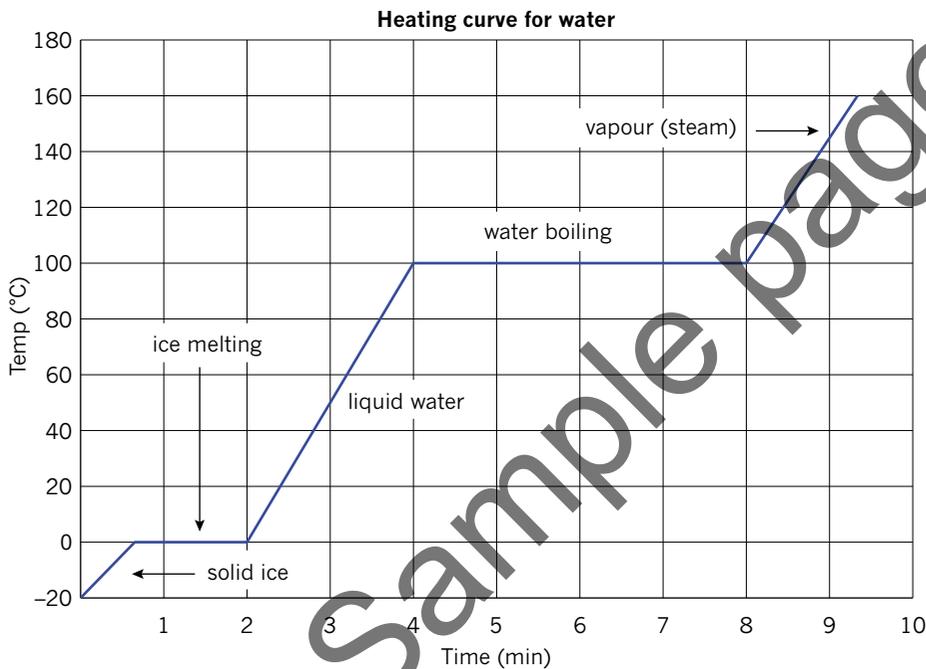


FIGURE 1.3.1 A heating curve for water.

Latent heat

The energy needed to change the state of a substance (e.g. solid to liquid, liquid to gas) is called latent heat. Latent heat is the 'hidden' energy that has to be added or removed from a material in order for the material to change state.

i The latent heat is calculated using the equation:

$$Q = mL$$

where Q is the heat energy transferred in joules (J)

m is the mass in kilograms (kg)

L is the latent heat (J kg^{-1}).

LATENT HEAT OF FUSION (MELTING)

As thermal energy is transferred to a solid, the temperature of the solid increases. The particles within the solid gain internal energy (as kinetic energy and some potential energy) and their speed of vibration increases. At the point where the solid begins to melt, the particles move further apart, reducing the strength of the bonds holding them in place. At this point, instead of increasing the temperature, the extra energy increases the potential energy of the particles, reducing the interparticle or intermolecular forces. No change in temperature occurs as all the extra energy supplied is used in reducing these forces between particles.

The amount of energy required to melt a solid is exactly the same as the amount of potential energy released when the liquid re-forms into a solid. It is termed the **latent heat of fusion**.

The amount of energy required will depend on the particular solid.

i For a given mass of a substance:

heat energy transferred = mass of substance \times specific latent heat of fusion

$$Q = mL_{\text{fusion}}$$

where Q is the heat energy transferred in joules (J)

m is the mass in kilograms (kg)

L_{fusion} is the latent heat of fusion in J kg^{-1} .

It takes almost 80 times as much energy to turn 1 kg of ice into water (with no temperature change) as it does to raise the temperature of 1 kg of water by 1°C . It takes a lot more energy to overcome the large intermolecular forces within the ice than it does to simply add kinetic energy in raising the temperature.

The latent heats of fusion for some common materials are shown in Table 1.3.1.

Worked example 1.3.1

LATENT HEAT OF FUSION

How much energy must be removed from 2.5 L of water at 0°C to produce a block of ice at 0°C ? Express your answer in kJ.	
Thinking	Working
Cooling from liquid to solid involves the latent heat of fusion, where the energy is removed from the water. Calculate the mass of water involved.	1 L of water = 1 kg, so 2.5 L = 2.5 kg
Use Table 1.3.1 to find the latent heat of fusion for water.	$L_{\text{fusion}} = 3.34 \times 10^5 \text{ J kg}^{-1}$
Use the equation $Q = mL_{\text{fusion}}$.	$Q = mL_{\text{fusion}}$ $= 2.5 \times 3.34 \times 10^5$ $= 8.35 \times 10^5 \text{ J}$
Convert to kJ.	$Q = 8.35 \times 10^2 \text{ kJ}$

Worked example: Try yourself 1.3.1

LATENT HEAT OF FUSION

How much energy must be removed from 5.5 kg of liquid lead at 327°C to produce a block of solid lead at 327°C ? Express your answer in kJ.

Substance	Melting point ($^\circ\text{C}$)	L_{fusion} (J kg^{-1})
water	0	3.34×10^5
oxygen	-219	0.14×10^5
lead	327	0.25×10^5
ethanol	-114	1.05×10^5
silver	961	0.88×10^5

TABLE 1.3.1 The latent heats of fusion for some common materials.

LATENT HEAT OF VAPORISATION (BOILING)

It takes much more energy to convert a liquid to a gas than it does to convert a solid to a liquid. This is because, to convert to a gas, the intermolecular bonds must be broken. During the change of state, the energy supplied is used solely in overcoming intermolecular bonds. The temperature will not rise until all of the material in the liquid state is converted to a gas, assuming that the liquid is evenly heated. For example, when liquid water is heated to boiling point, a large amount of energy is required to change its state from liquid to steam (gas). The temperature will remain at 100°C until all of the water has turned into steam. Once the water is completely converted to steam, then the temperature can start to rise again.

The amount of energy required to change a liquid to a gas is exactly the same as the potential energy released when the gas returns to a liquid. It is called the **latent heat of vaporisation**.

The amount of energy required will depend on the particular substance.

i For a given mass of a substance:

heat energy transferred = mass of substance × specific latent heat of vaporisation

$$Q = mL_{\text{vapour}}$$

where Q is the heat energy transferred in joules (J)

m is the mass in kilograms (kg)

L_{vapour} is the latent heat of vaporisation (J kg^{-1}).

Note that, in just about every case, the latent heat of vaporisation of a substance will be different to the latent heat of fusion for that substance. Some latent heat of vaporisation values are listed in Table 1.3.2.

In many instances, it is necessary to consider the energy required to heat a substance and also change its state. Problems like this are solved by considering the rise in temperature separately from the change of state.

Worked example 1.3.2

CHANGE IN TEMPERATURE AND STATE

50 mL of water is heated from a room temperature of 20°C to its boiling point at 100°C. It is boiled at this temperature until it is completely evaporated. How much energy in total was required to raise the temperature and boil the water?	
Thinking	Working
Calculate the mass of water involved.	50 mL of water = 0.05 kg
Find the specific heat capacity of water (see Table 1.2.1).	$c = 4200 \text{ J kg}^{-1} \text{ K}^{-1}$
Use the equation $Q = mc\Delta T$ to calculate the heat energy required to change the temperature of water from 20°C to 100°C.	$Q = mc\Delta T$ $= 0.05 \times 4200 \times (100 - 20)$ $= 16800 \text{ J}$
Find the specific latent heat of vaporisation of water.	$L_{\text{vapour}} = 22.5 \times 10^5 \text{ J kg}^{-1}$
Use the equation $Q = mL_{\text{vapour}}$ to calculate the latent heat required to boil water.	$Q = mL_{\text{vapour}}$ $= 0.05 \times 22.5 \times 10^5$ $= 112500 \text{ J}$
Find the total energy required to raise the temperature and change the state of the water.	$\text{Total } Q = 16800 + 112500$ $= 129300 \text{ J (or } 1.29 \times 10^5 \text{ J)}$

Substance	Boiling point (°C)	L_{vapour} (J kg^{-1})
water	100	22.5×10^5
oxygen	-183	2.2×10^5
lead	1750	9.0×10^5
ethanol	78	8.7×10^5
silver	2193	23.0×10^5

TABLE 1.3.2 The latent heat of vaporisation of some common materials.

PHYSICSFILE

Extinguishing fire

The latent heat of vaporisation of water is very high. This is due to the molecular structure of the water.

This characteristic of water makes it very useful for extinguishing fires.

That's because water can absorb vast amounts of thermal energy before it evaporates. By pouring water onto a fire, energy is transferred away from the fire to heat the water. Then, even more (in fact much more) heat is transferred away from the fire to convert the water into steam.

Worked example: Try yourself 1.3.2

CHANGE IN TEMPERATURE AND STATE

3 L of water is heated from a fridge temperature of 4°C to its boiling point at 100°C . It is boiled at this temperature until it is completely evaporated. How much energy in total was required to raise the temperature and boil the water?

EVAPORATION AND COOLING

If you spill some water on the floor then come back in a couple of hours, the water will probably be gone. It will have evaporated. It has changed from a liquid into a vapour at room temperature in a process called **evaporation**. The reason for this is that the water particles, if they have sufficient energy, are able to escape through the surface of the liquid into the air. Over time, no liquid remains.

Evaporation is more noticeable in **volatile** liquids such as methylated spirits, mineral turpentine, perfume and liquid paper. The surface bonds are weaker in these liquids and they evaporate rapidly. This is why you should never leave the lid off bottles of these liquids. They are often stored in narrow-necked bottles for this reason.

i The rate of evaporation of a liquid depends on:

- the volatility of the liquid: more-volatile liquids evaporate faster
- the surface area: greater evaporation occurs when greater surface areas are exposed to the air
- the temperature: hotter liquids evaporate faster
- the humidity: less evaporation occurs in more humid conditions
- air movement: if a breeze is blowing over the liquid's surface, evaporation is more rapid.

Whenever evaporation occurs, higher-energy particles escape the surface of the liquid, leaving the lower-energy particles behind, as is shown in Figure 1.3.2. As a result, the average kinetic energy of the particles remaining in the liquid drops and the temperature decreases. Humans use this cooling principle when sweating to stay cool. When rubbing alcohol is dabbed on your arm before an injection, the cooling of the volatile liquid numbs your skin.

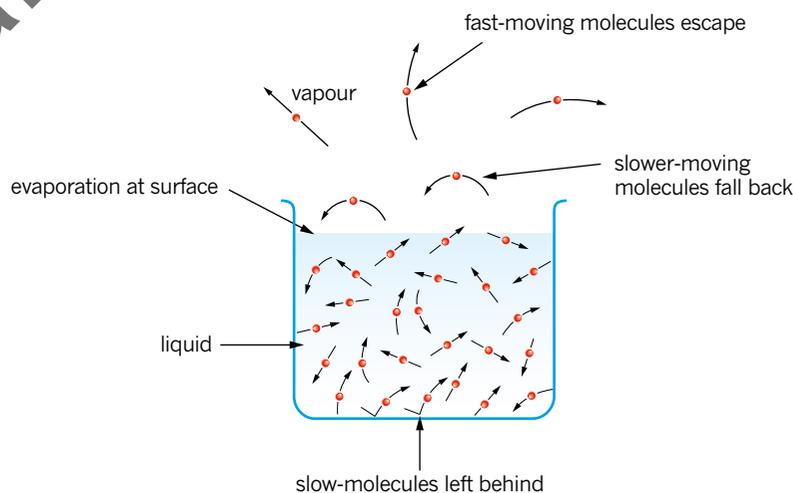


FIGURE 1.3.2 Fast-moving molecules with high kinetic energy can escape the liquid, leaving molecules with lower kinetic energy behind.

Other applications of evaporation such as evaporative coolers will be discussed in more detail in Chapter 2.

1.3 Review

SUMMARY

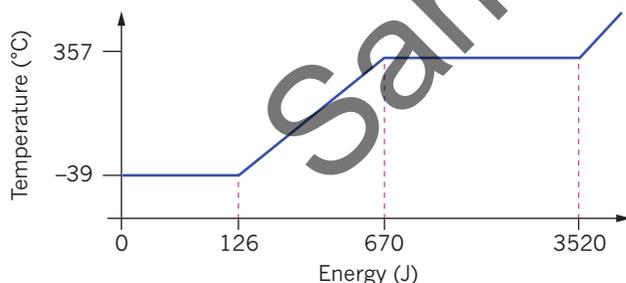
- When a solid material changes state, energy is needed to separate the particles by overcoming the attractive forces between the particles.
- Latent heat is the energy required to change the state of 1 kg of material at a constant temperature.
- In general, for any mass of material the energy required (or released) is
$$Q = mL$$
where Q is the energy transferred in joules (J)
 m is the mass in kilograms (kg)
 L is the latent heat (J kg^{-1}).
- The latent heat of fusion, L_{fusion} , is the energy required to change 1 kg of a material between the solid and liquid states.
- The latent heat of vaporisation, L_{vapour} , is the energy required to change 1 kg of a material between the liquid and gaseous states.
- The latent heat of fusion of a material will be different to (and usually less than) the latent heat of vaporisation for that material.
- Evaporation is when a liquid turns into gas at room temperature. The temperature of the liquid falls as this occurs.
- The rate of evaporation depends on the volatility, temperature and surface area of the liquid and the presence of a breeze.

KEY QUESTIONS

Refer to the values in Table 1.3.1 and Table 1.3.2 on pages 14 and 15. You may also need to refer to Table 1.2.1 on page 10.

The following information relates to questions 1 to 5.

The graph below represents the heating curve for mercury, a metal that is a liquid at normal room temperature. Thermal energy is added to 10 g of solid mercury, initially at a temperature of -39°C , until all of the mercury has evaporated.



- 1 Why does the temperature remain constant during the first part of the graph?
- 2 What is the melting point of mercury, in degrees Celsius?
- 3 What is the boiling point of mercury, in degrees Celsius?
- 4 From the graph, what is the latent heat of fusion of mercury?
- 5 From the graph, what is the latent heat of vaporisation of mercury?
- 6 How much heat energy must be transferred away from 100 g of steam at 100°C to change it completely to a liquid?
- 7 How many kJ of energy are required to melt exactly 100 g of ice initially at -4.00°C ? Assume no loss of energy to surroundings.
- 8 Which of the following explains why hot water in a spa-pool evaporates more rapidly than cold water?
 - A Hot water molecules have less energy than cold water molecules.
 - B Hot water molecules have more energy than cold water molecules.
 - C Hot water forms water vapour and bubbles to the surface.
 - D Hot water dissolves into the pool material more rapidly.
- 9 A painter spills some mineral turpentine onto a concrete floor. After a minute, most of the liquid is gone. Which of the following is correct?
 - A Most of the liquid has boiled, becoming hotter.
 - B Most of the liquid has evaporated and the remaining liquid becomes warmer as it does so.
 - C Most of the liquid has evaporated with no change in temperature of the remaining liquid.
 - D Most of the liquid has evaporated and the remaining liquid becomes colder as it does so.

1.4 Conduction



FIGURE 1.4.1 Emperor penguin chicks avoid heat loss through conduction by sitting on the adult's feet. In this way they avoid contact with the ice.

If two objects are at different temperatures and are in thermal contact (that is, they can exchange energy via heat processes), then thermal energy will transfer from the hotter object to the cooler object. Figure 1.4.1 shows how, by preventing the chick's thermal contact with the cold ice, this adult is able to protect the vulnerable penguin offspring.

There are three possible means by which heat can be transferred:

- conduction
- convection
- radiation.

This section focuses on conduction.

CONDUCTORS AND INSULATORS

Conduction is the process by which heat is transferred from one place to another without the net movement of particles (atoms or molecules). Conduction can occur within a material or between materials that are in thermal contact. For example, if one end of a steel rod is placed in a fire, heat will travel along the rod so that the far end of the rod will also heat up; or if a person holds an ice cube, then heat will travel from their hand to the ice.

While all materials will conduct heat to some extent, this process is most significant in solids. It is important in liquids but plays a lesser role in the movement of energy in gases.

Materials that conduct heat readily are referred to as good **conductors**. Materials that are poor conductors of heat are referred to as **insulators**. An example of a good conductor and a good insulator can be seen in Figure 1.4.2.

In secondary physics, the terms 'conductor' and 'insulator' are used in the context of both electricity and heating processes. What makes a material a good conductor of heat doesn't necessarily make it a good conductor of electricity. The two types of conduction are related but it's important not to confuse the two processes. A material's ability to conduct heat depends on how conduction occurs within the material.

Conduction can happen in two ways:

- energy transfer through molecular or atomic collisions
- energy transfer by free electrons.

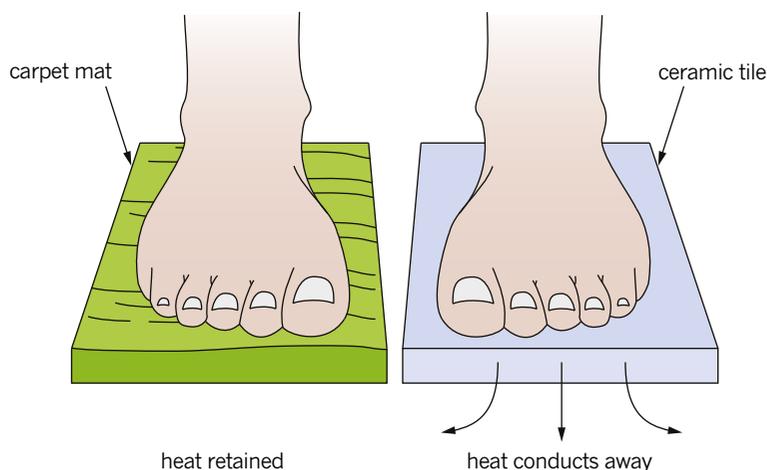


FIGURE 1.4.2 Ceramic floor tiles are good conductors of heat. They conduct heat away from the foot readily and so your feet feel cold on tiles. The carpet mat is a thermal insulator. Thermal energy from the foot is not transferred away as quickly and so your foot doesn't feel as cold.

THERMAL TRANSFER BY COLLISION

The kinetic particle model explains that particles in a solid substance are constantly vibrating within the material structure and so interact with neighbouring particles. If one part of the material is heated, then the particles in that region will vibrate more rapidly. Interactions with neighbouring particles will pass on this kinetic energy throughout the system via the bonds between the particles (see Figure 1.4.3).

The process can be quite slow since the mass of the particles is relatively large and the vibrational velocities are fairly low. Materials for which this method of conduction is the only means of heat transfer are likely to be poor conductors of heat or even thermal insulators. Materials such as glass, wood and paper are poor conductors of heat.

THERMAL TRANSFER BY FREE ELECTRONS

Some materials, particularly metals, have electrons that are not directly involved in any one particular chemical bond. Therefore, these electrons are free to move throughout the lattice of positive ions.

For example, if a metal is heated, then not only will the positive ions within the metal gain extra energy but so will these free electrons. As the electron's mass is considerably less than the positive ions, even a small energy gain will result in a very large gain in velocity. Consequently, these free electrons provide a means by which heat can be quickly transferred throughout the whole of the material. It is therefore no surprise that metals, which are good electrical conductors because of these free electrons, are also good thermal conductors.

THERMAL CONDUCTIVITY

Thermal conductivity describes the ability of a material to conduct heat. It is temperature dependent and is measured in watts per metre kelvin ($\text{W m}^{-1} \text{K}^{-1}$). Table 1.4.1 highlights the difference in conductivity in metals compared with other substances.

Material	Conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
silver	420
copper	380
aluminium	240
steel	60
ice	2.2
brick, glass	≈ 1
concrete	≈ 1 (depending on composition)
water	0.6
human tissue	0.2
wood	0.15
polystyrene	0.08
paper	0.06
fibreglass	0.04
air	0.025

TABLE 1.4.1 Thermal conductivities of some common materials.

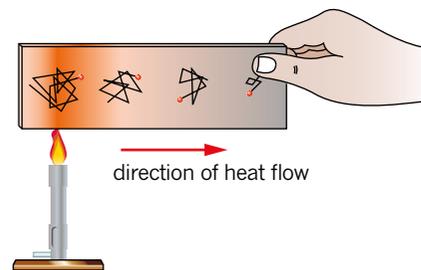


FIGURE 1.4.3 Thermal energy is passed on by collisions between adjacent particles.

Factors affecting thermal conduction

The rate at which heat will be transferred through a system depends on the:

- nature of the material. The larger a material's thermal conductivity, the more rapidly it will conduct heat energy.
- temperature difference between the two objects. A greater temperature difference will result in a faster rate of energy transfer.
- thickness of the material. Thicker materials require a greater number of collisions between particles or movement of electrons to transfer energy from one side to the other.
- surface area. Increasing the surface area relative to the volume of a system increases the number of particles involved in the transfer process, increasing the rate of conduction.

The rate at which heat is transferred is measured in joules per second (J s^{-1}), or watts (W).

PHYSICSFILE

Igloos

It seems strange that an igloo can keep a person warm when ice is so cold. Igloos are constructed from compressed snow that contains many air pockets. The air in these pockets is a poor conductor of heat, which means heat inside the igloo is not easily transferred away. The body heat of the occupant, as well as that of his or her small heat source, is trapped inside the igloo and able to keep them warm.



EXTENSION

Thermal conductivity

The rate of energy transfer by conduction (energy per unit time) through a material can be calculated using:

$$\frac{Q}{t} = \frac{kA\Delta T}{L}$$

where $\frac{Q}{t}$ is the heat energy transferred in joules (J) per unit time, t , in seconds (s)

k is the thermal conductivity of the material ($\text{W m}^{-1} \text{K}^{-1}$)

A is the surface area in metres squared perpendicular to the direction of heat flow (m^2)

ΔT is the temperature difference across the material in kelvin or degrees Celsius (K or $^{\circ}\text{C}$)

L is the thickness of the material through which the heat is being transferred in metres (m).

Designers use this relationship when calculating the insulating ability of the fill inside clothing such as parkas. Architects and builders use it to calculate the efficiency of building insulation.

Guidelines exist to ensure the efficiency of insulating materials. Building materials that limit the transfer of heat help to keep houses warm in winter and cool in summer. This saves money and helps to reduce carbon dioxide emissions from the use of gas or electricity to heat houses.

1.4 Review

SUMMARY

- Conduction is the process of heat transfer within a material or between materials without the overall transfer of the substance itself.
- All materials will conduct heat to a greater or lesser degree. Materials that readily conduct heat are called good thermal conductors. Materials that conduct heat poorly are called thermal insulators.
- Whether a material is a good conductor depends on the method of conduction:
 - Heat transfer by molecular collisions alone occurs in poor to very poor conductors.
 - Heat transfer by molecular collisions and free electrons occurs in good to very good conductors.
- The rate of conduction depends on the temperature difference between two materials, the thickness of the material, the surface area and the nature of the material.

KEY QUESTIONS

- 1 Explain why the process of conduction by molecular collision is slow.
- 2 Why are metals more likely to conduct heat than wood?
- 3 List the properties of a material that affect its ability to conduct heat.
- 4 Stainless steel saucepans are often manufactured with a copper base. What is the most likely reason for this?
- 5 One way of making a house energy-efficient is to use double-glazed windows. These consist of two panes of glass with air trapped in between the panes. On a hot day, the energy from the hot air outside the house is not able to penetrate the air gap and so the house stays cool.

Which of the following best explains why double-glazing works?

 - A Air is a conductor of heat and so the thermal energy is able to pass through.
 - B Air is a conductor of heat and so the thermal energy is not able to pass through.
 - C Air is an insulator of heat and so the thermal energy is not able to pass through.
 - D Air is an insulator of heat and so the thermal energy is able to pass through.
- 6 How does a down-filled quilt keep a person warm in winter?
- 7 Fibreglass insulation batts are thick and lightweight, and they make a house more energy-efficient. On a cold July night, the external temperature in the roof of an insulated house is 6°C. The air temperature near the ceiling inside the house is 20°C.

Complete the paragraph below by choosing the correct response from the choices given in brackets to explain the effects of ceiling insulation in this situation. The insulation batts stop the thermal energy from **[escaping/entering]** the house. The air in the batts has **[high/low]** conductivity and the thermal energy is **[able/not able]** from escape from the house.
- 8 On a cold day, the plastic or rubber handles of a bicycle feel much warmer than the metal surfaces. Explain this in terms of the thermal conductivity of each material.

1.5 Convection

This section will investigate convection, which is the transfer of thermal energy within a fluid (liquid or a gas) by the movement of hot areas from one place to another. Unlike other forms of heat transfer such as conduction and radiation, convection involves the mass movement of particles within a system over a distance that can be quite considerable.

HEATING BY CONVECTION

Although liquids and gases are generally not very good conductors of thermal energy, heat can be transferred quite quickly through liquids and gases by convection. Unlike other forms of thermal energy transfer, **convection** involves the mass movement of particles within a system over a distance.

As a fluid is heated, the particles within it gain kinetic energy and push apart due to the increased vibration of the particles. This causes the density of the heated fluid to decrease and the heated fluid rises. Colder fluid, with slower moving particles, is more dense and heavier and hence falls, moving in to take the place of the warmer fluid. A convection current forms when there is warm fluid rising and cool fluid falling. This action can be seen in Figure 1.5.1. Upwellings in oceans, wind and weather patterns are at least partially due to convection on a very large scale.

It is difficult to quantify the thermal energy transferred via convection but some estimates can be made. The rate at which convection will occur is affected by:

- the temperature difference between the heat source and the convective fluid
- the surface area exposed to the convective fluid.

In a container, the effectiveness of convection to transfer heat depends on the placement of the source of heat. For example, the heating element in a kettle is always found near the bottom of the kettle. From this position, convection currents form throughout the water to heat it more effectively (see Figure 1.5.2(a)). If the heating element is placed near the top of the kettle, convection currents form only near the top. This is because the hotter water is less dense than the cooler water below and will remain near the top. Convection currents will not form throughout the water (see Figure 1.5.2(b)).

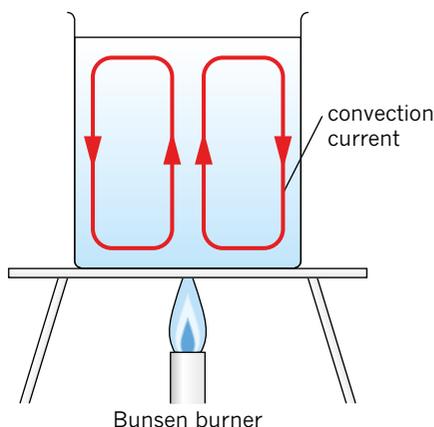


FIGURE 1.5.1 When a liquid or gas is heated, it becomes hotter and less dense so will rise. The colder, denser fluid will fall. As this fluid heats up, it in turn will rise, creating a convection current.

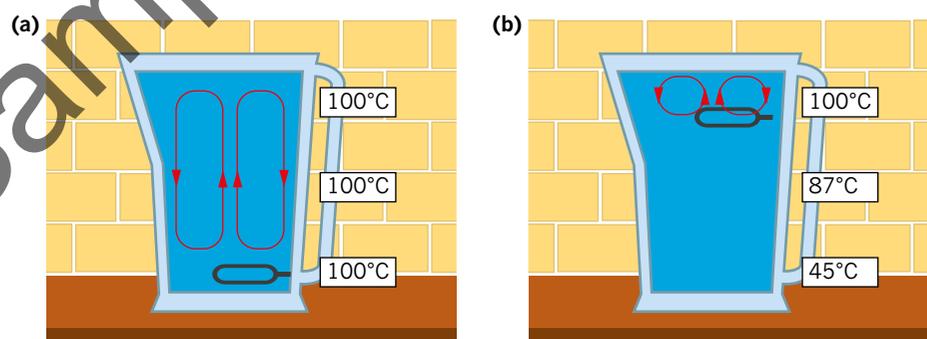


FIGURE 1.5.2 (a) By placing the heating element at the bottom of a kettle, the water near the bottom is heated and rises, forming convection currents throughout the entire depth of the water. (b) If the heating element is placed near the top of the kettle, the convection currents form near the top and heat transfer is slower.

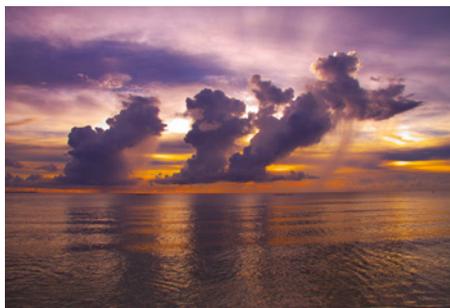


FIGURE 1.5.3 The thunderheads of summer storms are a very visible indication of natural convection in action.

There are two main causes of convection:

- forced convection, for example ducted heating in which air is heated and then blown into a room
- natural convection, such as that illustrated in Figure 1.5.1, when a fluid rises as it is heated.

A dramatic example of natural convection is the thunderhead clouds of summer storms (as seen in Figure 1.5.3), which form when hot, humid air from natural convection currents is carried rapidly upwards into the cooler upper atmosphere.

PHYSICS IN ACTION

Wind chill

Convective effects are the main means of heat transfer that lead to the 'wind chill' factor. The wind blows away the thin layer of relatively still air near the skin that would normally act as a partial insulator in still air. Cooler air comes in closer contact with the skin and heat loss increases. It feels as if the 'effective' temperature of the surrounding air has decreased. Skiers can experience similar effects simply from the wind created by their own motion.

In cold climates the wind chill factor can become an important factor to consider. The chilling effect is even more dramatic when the body or clothing is wet, increasing evaporative cooling. Bushwalkers look for clothing that dries rapidly after rain and which carries moisture from the perspiration of heavy exertion away from the skin.

PHYSICSFILE

Paragliders

Paragliders fly by sitting in a harness suspended beneath a fabric wing. They gain altitude by catching thermals. Thermals are columns of rising hot air created by dark regions on the ground that have been heated up by the Sun. Roads, rock faces and ploughed fields are good at creating thermals.

In 2007, Polish paraglider Ewa Wisnierska was practising in NSW for a competition when she was caught in an intense thermal updraught during a storm. She reached an altitude of almost 10 km. Fortunately, she lost altitude, and landed about 60 km from where she started, where her crew found and rescued her. Ewa is now a paragliding instructor in Germany.



FIGURE 1.5.4 Paragliders can gain altitude by finding a thermal. These are areas of rising hot air created by hot regions on the ground. These paragliders are flying near Bright, Victoria.

1.5 Review

SUMMARY

- Convection is the transfer of heat within a fluid (liquid or gas).
- Convection involves the mass movement of particles within a system over a distance.
- A convection current forms when there is warm fluid rising and cool fluid falling.

KEY QUESTIONS

- 1 Through what states of matter can convection occur?
- 2 In which direction does the transfer of heat in a convection current initially flow?
- 3 Pilots of glider aircraft or hang-gliders, some birds such as eagles and some insects rely on 'thermals' to give them extra lift. Explain how these rising columns of air are established.
- 4 Which of the following statements about liquids and gases is true?
 - A Liquids and gases can transfer heat quite slowly through convection even though liquids and gases are very good conductors of thermal energy.
 - B Liquids and gases can transfer heat quite quickly through conduction because liquids and gases are very good conductors of thermal energy.
 - C Liquids and gases can transfer heat quite quickly through convection because liquids and gases are very good conductors of thermal energy.
 - D Liquids and gases can transfer heat quite quickly through convection even though liquids and gases are not very good conductors of thermal energy.
- 5 Convection is referred to as a method of heat transfer through fluids. Explain whether it is possible for solids to pass on their heat energy by convection.
- 6 On a hot day, the top layer of water in a swimming pool can heat up while the lower, deeper parts of the water can remain quite cold. Explain, using the concept of convection, why this happens.

1.6 Radiation

Both convection and conduction involve the transfer of heat through matter. Life on Earth depends upon the transfer of energy from the Sun through the near-vacuum of space. If heat could only be transferred by the action of particles, then the Sun's energy would never reach Earth. Radiation is a means of transfer of heat without the movement of matter.

RADIATION

In this context, **radiation** is a shortened form of electromagnetic radiation, which includes visible, ultraviolet and infrared light. Together with other forms of light, these make up the **electromagnetic spectrum**.

The transfer of heat from one place to another without the movement of particles is by electromagnetic radiation. Electromagnetic radiation travels at the speed of light. When electromagnetic radiation (light) hits an object, it will be partially reflected, partially transmitted and partially **absorbed**. The absorbed part transfers thermal energy to the absorbing object and causes a rise in temperature. When you hold a marshmallow by an open fire, you are using radiation to toast the marshmallow, as shown in Figure 1.6.1.

Electromagnetic radiation is **emitted** by all objects that are at a temperature above absolute zero (0 K or -273°C). The **wavelength** and **frequency** of the emitted radiation depends on the internal energy of the object. The higher the temperature of the object, the higher the frequency and the shorter the wavelength of the radiation emitted. This can be seen in Figure 1.6.2.



FIGURE 1.6.1 Heat transfer from the flame to the marshmallow is an example of radiation.

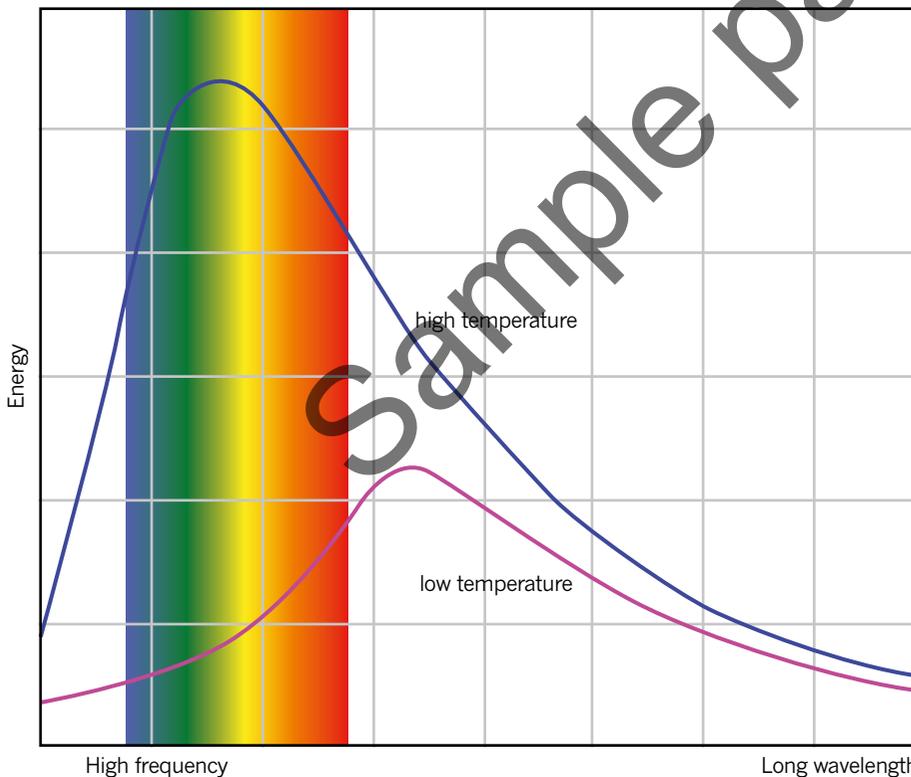


FIGURE 1.6.2 A system emits radiation over a range of frequencies. At a low temperature, it will emit small amounts of radiation of longer wavelengths. As the temperature of the system increases, more short-wavelength radiation is emitted and the total radiant energy emitted increases.

A human body emits radiation in the infrared range of wavelengths, while hotter objects emit radiation of a higher frequency and shorter wavelength. Hotter objects can emit radiation in the range of visible, ultraviolet and shorter wavelengths of the electromagnetic spectrum. For example, as a red-hot fire poker heats up further, it becomes yellow-hot.

EMISSION AND ABSORPTION OF RADIANT ENERGY

All objects both absorb and emit thermal energy by radiation. If an object absorbs more thermal energy than it emits, its temperature will increase. If an object emits more energy than it absorbs, its temperature will decrease. If no temperature change occurs, the object and its surroundings are in thermal equilibrium.

While all objects emit some radiation, they will not all emit or absorb at the same rate.

A number of factors affect both the rate of emission and the rate of absorption.

- Surface area—the larger the exposed surface area, the higher the rate of radiant transfer.
- Temperature—the greater the difference between the temperature of the absorbing or emitting surface and the temperature of the surrounding objects, the greater the rate of energy transfer by radiation.
- Wavelength of the **incident** radiation—matte black surfaces are almost perfect absorbers of radiant energy at all wavelengths. Highly reflective surfaces are good reflectors of all wavelengths. An example of how reflective surfaces can be exploited is shown in Figure 1.6.3. For all other surfaces, the absorption of particular wavelengths of radiant energy will be affected by the wavelength of that energy. For example, although white surfaces absorb visible wavelengths of radiant energy poorly, white surfaces will absorb infrared radiation just as well as black surfaces do.
- Surface colour and texture—the characteristics of the surface itself determine how readily that particular surface will emit or absorb radiant energy.

Matte black surfaces will absorb and emit radiant energy faster than shiny, white surfaces. This means that a roughened, dark surface will heat up faster than a shiny, light one. Matte black objects will also cool down faster since they will radiate energy just as efficiently as they absorb energy. Car radiators are painted black to increase the emission by radiation of the thermal energy that is collected from the car engine.



FIGURE 1.6.3 The silvered surface of an emergency blanket reflects thermal energy back to the body, and retains the radiant energy, which would normally be lost. This simple method works as excellent thermal insulation.

PHYSICSFILE

Thermal imaging

All objects emit radiant energy. Humans are warm-blooded and emit radiation in the infrared region of the electromagnetic spectrum. This radiation is not visible to us, but can be detected using thermal imaging devices or night-vision goggles. These devices are used by the military for surveillance, and by search and rescue personnel. Some animals, notably some varieties of bugs, are able to detect infrared radiation.



FIGURE 1.6.4 This person is difficult to see normally (a), but they are warmer than the trees surrounding them and produce a stronger infrared emission, which the thermal imaging device is able to detect (b).

PHYSICSFILE

Heat loss in humans

It is estimated that, at normal room temperature, about 50 per cent of a person's heat loss is by radiation.

1.6 Review

SUMMARY

- Any object whose temperature is greater than absolute zero emits thermal energy by radiation.
- Radiant transfer of thermal energy from one place to another occurs by means of electromagnetic waves.
- When electromagnetic radiation falls on an object, it will be partially reflected, partially transmitted and partially absorbed.
- The rate of emission or absorption of radiant heat will depend upon the:
 - temperature difference between the object and the surrounding environment
 - surface area and surface characteristics of the object
 - wavelength of the radiation.

KEY QUESTIONS

- 1 Light is shone on an object.
 - a List three interactions that can occur between the light and the object.
 - b Which of the interactions from part (a) are associated with a rise in temperature?
- 2 The wavelength and frequency of emitted radiation depends on the internal energy of an object. Complete the sentences below by choosing the correct option from those provided in the brackets.

The higher the temperature of the object, the [**higher/lower**] the frequency and the [**longer/shorter**] the wavelength of the radiation emitted. For example, if a particular object emits radiation in the visible range, a cooler object could emit light in the [**infrared/ultraviolet**] range of the electromagnetic spectrum.
- 3 Which of the following will affect the rate at which an object radiates thermal energy?
 - A its temperature
 - B its colour
 - C its surface nature (shiny or dull)
 - D none of these
 - E all of A–C
- 4 Why is it impossible for heat to travel from the Sun to the Earth by conduction or convection?
- 5 Thermal imaging technology can be used to locate people lost in the Australian bush. How can thermal imaging technology 'see' people when the naked eye cannot?
- 6 Three identical, sealed beakers are filled with near-boiling water. One beaker is painted matte black, one is dull white and the third is gloss white.
 - a Which beaker will cool fastest?
 - b Which beaker will cool slowest?
- 7 Computer chips generate a lot of thermal energy that must be dispersed for the computer to function efficiently. Devices called heat sinks are used to help this process. What would you predict the heat sinks to be made of?

Chapter review

01

KEY TERMS

absolute zero	heat	potential energy
absorption	incident	radiation
conduction	insulator	specific heat capacity
conductor	internal energy	temperature
convection	kelvin	thermal contact
electromagnetic spectrum	kinetic energy	thermal energy
emission	kinetic particle model	thermal equilibrium
emit	latent heat	volatile
evaporation	latent heat of fusion	wavelength
frequency	latent heat of vaporisation	work

- According to the kinetic particle model, which of the following can be said of particles of matter?
 - They are in constant motion.
 - They have different sizes.
 - They have different shapes.
 - They are always floating.
- What does the kelvin scale measure?
- How does temperature differ from heat?
- Convert:
 - 5°C to kelvin
 - 200 K to °C.
- The specific heat capacity of iron is approximately half that of aluminium. A ball of iron and a ball of aluminium, both at 80°C, are dropped into a thermally insulated jar that contains a mass of water, equal to that of the balls, at 20°C. Thermal equilibrium is eventually reached. Describe the final temperatures of each of the metal balls.
- Two cubes, one silver and one iron, have the same mass and temperature. A quantity Q of heat is removed from each cube. Which one of the following properties causes the final temperatures of the cubes to be different?
 - density
 - specific heat capacity
 - latent heat of vaporisation
 - volume
- A solid substance is heated but its temperature does not change. Explain what is occurring.
- Which possesses the greater internal energy—1 kg of water boiling at 100°C or 1 kg of steam at 100°C? Explain why.
- A liquid is evaporating, causing the liquid to cool. Explain why the temperature of the liquid decreases.
- A 2.00 kg metal object requires 5.02×10^3 J of heat to raise its temperature from 20.0°C to 40.0°C. What is the specific heat capacity of the metal in $\text{J kg}^{-1} \text{K}^{-1}$? Give your answer to the nearest whole number.
- How many joules of energy are required to melt exactly 80 g of silver? ($L_{\text{fusion}} = 0.88 \times 10^5 \text{ J kg}^{-1}$) Give your answer to two significant figures.
- An insulated container holding 4.55 kg of ice at 0.00°C has 2.65 MJ of work done on it, while a heater provides 14 600 J of heat to the ice. If the latent heat of fusion of ice is $3.34 \times 10^5 \text{ J kg}^{-1}$, calculate the final temperature of the water. Assume that the increase in internal energy is first due to an increase in the potential energy and then an increase in the kinetic energy.
- An ice-cube that is sitting on a block of polystyrene at room temperature (20°C) melts very slowly. An ice-cube sitting on a metal pan also at room temperature melts very rapidly. Explain why this is so and why the metal feels colder to touch, even though it is the same temperature as the polystyrene.
- On a hot day when you sweat, your body feels cooler when a breeze is blowing. Explain why this happens.
- A vacuum flask has a tight-fitting stopper at the top. Its walls are made up of an inner and outer layer, which are shiny and are separated by a layer of air. Describe how this design makes a vacuum flask good at keeping liquids hot inside.
- Hypothermia is the cooling of the body to levels considerably lower than normal. The body's functions slow and death can result. A person may survive 12 hours in air at 0°C before suffering hypothermia, but may survive only a few minutes in water at 0°C. Explain why this is so and how wetsuits can help you survive in cold water.