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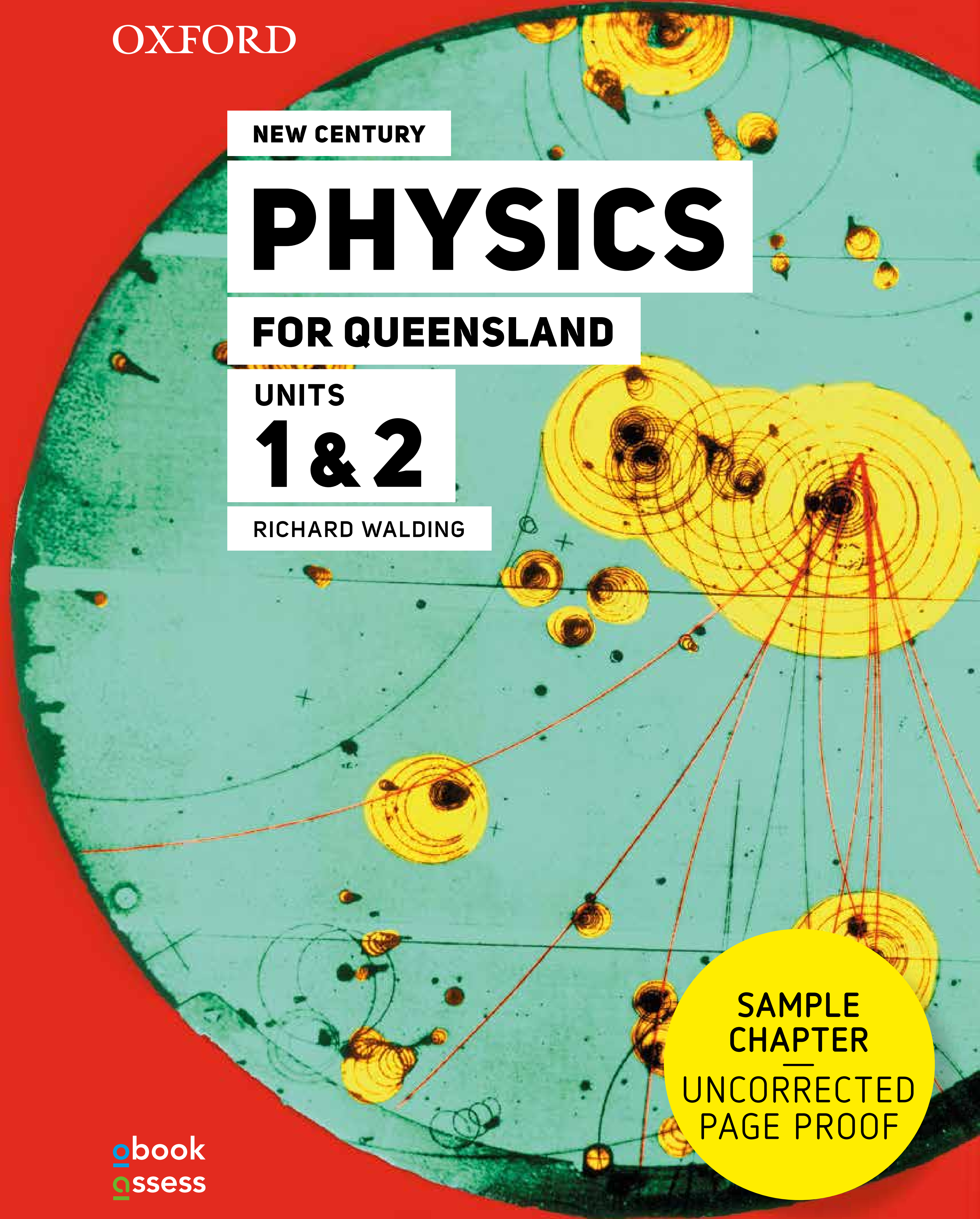

NEW CENTURY

PHYSICS

FOR QUEENSLAND

UNITS 1 & 2

RICHARD WALDING

SAMPLE CHAPTER
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CONTENTS

UNIT

1

THERMAL, NUCLEAR AND ELECTRICAL PHYSICS

The three seemingly different ideas of heat, nuclear energy and electricity have one thing in common - the pivotal role of energy in modern society. These three topics provide an introduction to the fundamental idea of energy transfers and transformations and how global energy needs are met.

As objects are heated their energy increases and this means changes to their internal energy - the microscopic kinetic and potential energy of the particles. An understanding of this internal energy forms the basis of modern thermodynamics and the laws that allow us to predict the direction of the flow of energy, deduce the source of energy losses and calculate the efficiency of energy transfer in devices such as car engines, steam engines and refrigerators.

This leads into an examination of matter at the atomic scale starting with the structure of the nucleus and how the strong nuclear force and electrostatic forces compete to keep the nucleus together or let it disintegrate into alpha, beta and nuclear radiation along with neutrinos and anti-neutrinos. We see how a decaying nucleus converts mass into energy as described by Einstein's famous equation $E = mc^2$ and how this process is the basis for nuclear reactors, radiopharmaceuticals and the stars. The final topic looks at electricity beginning with the relationship between voltage, current and resistance. Use of circuit analysis helps understand how electrical energy is transferred in wires to be used and controlled in homes and workplaces.

Topic 1 - Heating processes

Topic 1 - Heating processes	Chapters 1–3
Topic 2 - Ionising radiation and nuclear reactions	Chapters 4–6
Topic 3 - Electrical currents	Chapters 7–9

Unit objectives

- → Describe and explain heating processes, ionising radiation and nuclear reactions, and electrical circuits
- → Apply understanding of heating processes, ionising radiation and nuclear reactions, and electrical circuits
- → Analyse evidence about heating processes, ionising radiation and nuclear reactions, and electrical circuits
- → Interpret evidence about heating processes, ionising radiation and nuclear reactions, and electrical circuits
- → Investigate phenomena associated with heating processes, ionising radiation and nuclear reactions, and electrical circuits
- → Evaluate processes, claims and conclusions about heating processes, ionising radiation and nuclear reactions, and electrical circuits
- → Communicate understandings, findings, arguments and conclusions about heating processes, ionising radiation and nuclear reactions, and electrical circuits

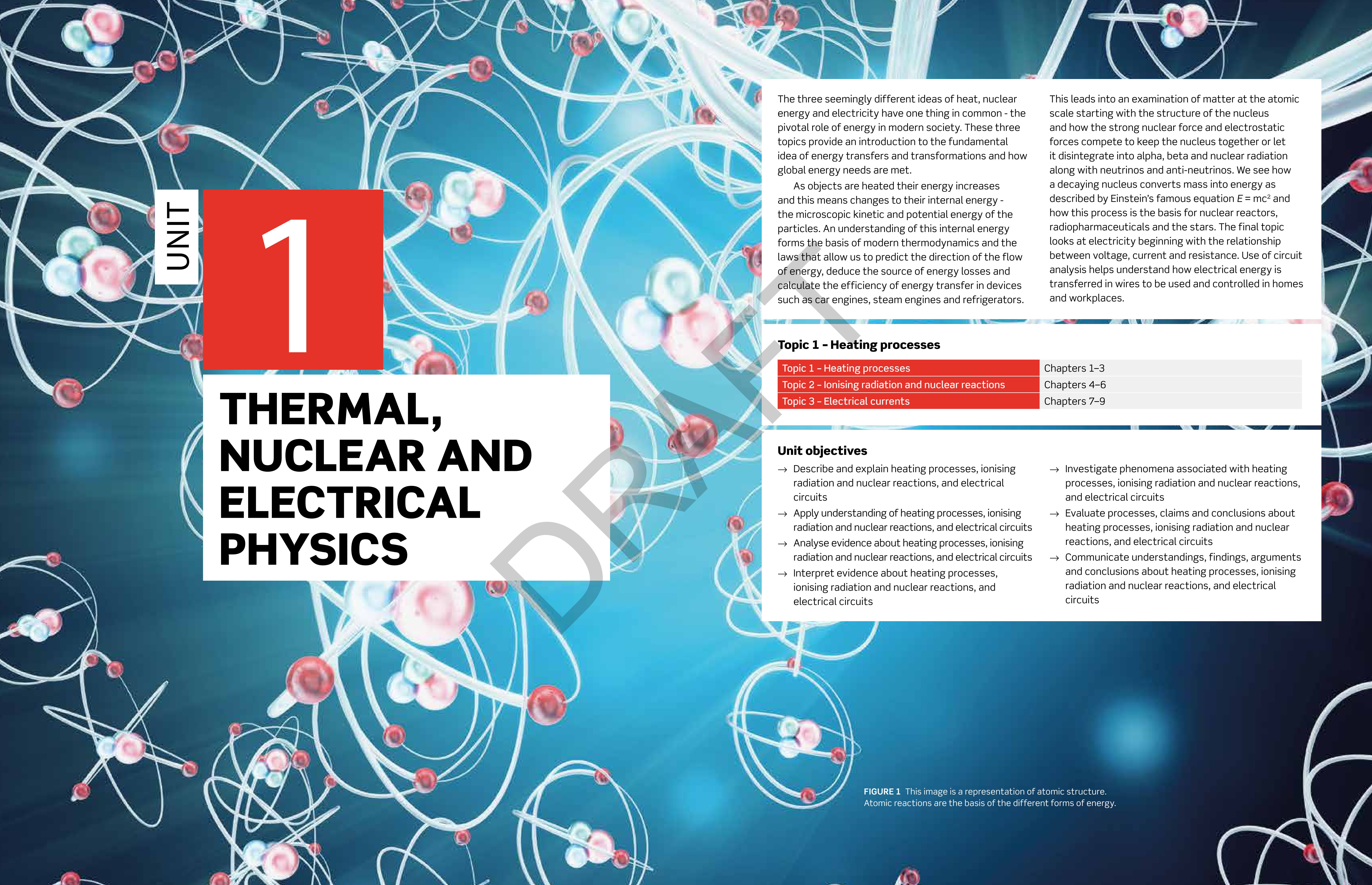

FIGURE 1 This image is a representation of atomic structure. Atomic reactions are the basis of the different forms of energy.

CHAPTER 1

Heat and temperature

Would you rather be too hot or too cold? If you're too hot, you can sit in the shade or wear fewer clothes, but that's about it. If you're too cold, you can add extra layers of clothing. But what is more important to survival: heat, or the lack of heat? The answer to each of these questions has to do with the internal structure of matter and how it responds to heat. It's a subject called 'thermodynamics'.

The term 'thermodynamics' stems from the Greek *therme* meaning 'heat' and *dynamis* meaning 'power', which was appropriate for the 1800s when it was first used as people were concerned about how to convert heat into power for factories and mines. Today, we say that **thermodynamics is concerned with systems involving energy transfer in the form of heat and work.** This includes applications such as solar heating and cooling of buildings, refrigeration and air-conditioning, and the design and construction of engines. To understand how matter behaves when heated, we need to consider the makeup of matter in terms of its particles – its microscopic nature.

MAKES YOU WONDER

In this chapter we will be examining some aspects of atoms that will help to answer questions such as:

→ What is heat? People talk about 'heat flow', but what flows?
→ Heat from the Sun and the cold of winter have always affected living conditions. What sense is more important for survival: the ability to feel heat and cold, the ability to see light, or the ability to hear sound? If you had to lose one, which one would it be?
→ Why does sucking an ice block make you feel cool? How does a cold tongue cool you down?
→ On a very hot day at the beach, why does walking on dark sand burn your feet but white sand is okay?
→ How can someone walk barefoot on coals at 400°C but standing on a hot road at 60°C burns their feet?
→ It is said that water molecules vibrate, but have you ever seen the molecules vibrate?
→ Temperature change initiates breathing when a child is born, so why are delivery rooms are heated? Shouldn't delivery rooms be cold so the reflex works even better?
→ Why can you smell if a gas tap has been left on when you walk into a laboratory, but you cannot smell the water spilt on the bench?
→ What's the hottest place on Earth, and what's the coldest? What are the maximum and minimum temperatures ever recorded experimentally on Earth?
→ Are heat and temperature the same thing? More heat, bigger temperature. What do they have in common?
→ What has more heat: a cup of coffee or a swimming pool?
→ Do heat and cold flow like liquids? Heat seems to 'run' from hot to cold. What do hot and cold have in common with a liquid?

OBJECTIVES

By the end of this chapter, you should be able to:
→ describe the kinetic particle model of matter
→ define and distinguish between thermal energy, temperature, kinetic energy, heat and internal energy
→ use $T_K = T_C + 273$ to convert temperature measurements between Celsius and Kelvin
→ use digital and other measuring devices to collect data, ensuring measurements are recorded using the correct symbol, SI unit, number of significant figures and associated measurement uncertainty (absolute and percentage); all experimental measurements should be recorded in this way.

PRACTICALS

MANDATORY PRACTICAL	**1.1** Heat and temperature change – electric kettle
MANDATORY PRACTICAL	**1.4** Factors affecting the temperature of water being heated up

FIGURE 1 Why is it cooler in the shade?

MANDATORY PRACTICAL

1.1 Heat and temperature change – electric kettle
Go to page xxx »

1.1 Heating and cooling

KEY IDEAS

In this section, you will learn about:
+ the definition of heat and energy
+ how we feel heat.

heat
the internal energy transferred throughout the heating process

energy
the capacity to do mechanical work; the higher the energy content the greater the impact when it is transformed or transferred

The focus of this chapter is both the term **heat** and various forms of **energy**, such as thermal, kinetic and internal, and its effect on matter.

Heat is energy in the process of being transferred from one place to another due to temperature difference. Because heat, like 'work', is a quantity of energy being transferred between two bodies, neither body has a definite amount of heat. Instead, they have a definite amount of energy. In the same way, a body doesn't have a certain amount of 'work'. It has energy, and when it transfers this energy we say work is being done. 'Heat' is not a thing – it is a process. Energy is the capacity to do work. The higher the energy content, the greater the effect when it is transformed or transferred.

The idea of heat has developed through three different models over time. Thousands of years ago, heat was thought to be something alive and living inside things. This was the *animistic* (animal-like) view. This changed with the Greek *substantialist* idea 2000 years ago that heat was a material substance (called 'caloric') that was lost or gained as an object was heated or cooled. Our modern *kinetic* view started in the mid-1800s when heat became regarded as the transfer of energy related to the movement of microscopic particles (atoms and molecules). The word 'energy' was given in 1852 by William Thomson (Lord Kelvin) from Glasgow, Scotland. This is where we are today: 'energy' is not a thing – it is a property of an object.

How do we 'feel' heat?

Steam feels hot, but ice feels cold. We have receptors (called thermoreceptors) in our skin that tell us if something is hot or cold. The breakthrough research on this was done by New Zealand scientist Dr Ainsley Iggo in 1959. He anaesthetised 15 cats and exposed the nerves in their legs. By placing hot and cold metal pins on certain nerves he found that there were different receptors for hot and for cold. The hot ones had a thin myelin sheath on the axon so the electrical signal to the spinal cord was slow. The cold ones had a thicker sheath and the signals were faster. That's why you respond faster to a cold stimulus than a hot one.

CHECK YOUR LEARNING 1.1

Describe and explain

1 Describe the difference between heat and energy.

2 Explain why heat is described as a process.

3 Describe how we feel the heat.

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1.2 The kinetic particle theory of matter

KEY IDEAS

In this section, you will learn about:
+ the kinetic particle theory of matter
+ the characteristics of solids, liquids and gases as states of matter.

atoms
the smallest particle of a chemical element that can exist

We take it for granted that matter is made of **atoms**. The earliest people to make this claim were the Greek philosophers Leucippus and Democritus (about 2500 years ago), who suggested that matter consisted of small, hard particles that couldn't be cut up. They called the particles atoms (Greek *a* = 'not', *toma* = 'cut'). This idea of particles gave rise to what we know as solids, liquid and gases – the three states of matter, sometimes called the three 'phases' of matter.

States of matter

Solids, liquids and gases feel different and behave differently. They can be hard, soft, runny or invisible. They can blow like the wind, flow like a river or just sit still. An understanding of how particles are arranged in the states of matter can help us understand their properties – in this case, what happens when they get hot, or when hot and cold are mixed. Figure 1 shows a simple diagram of the three states of matter. But to make sense of their properties we need to look at each state in detail.

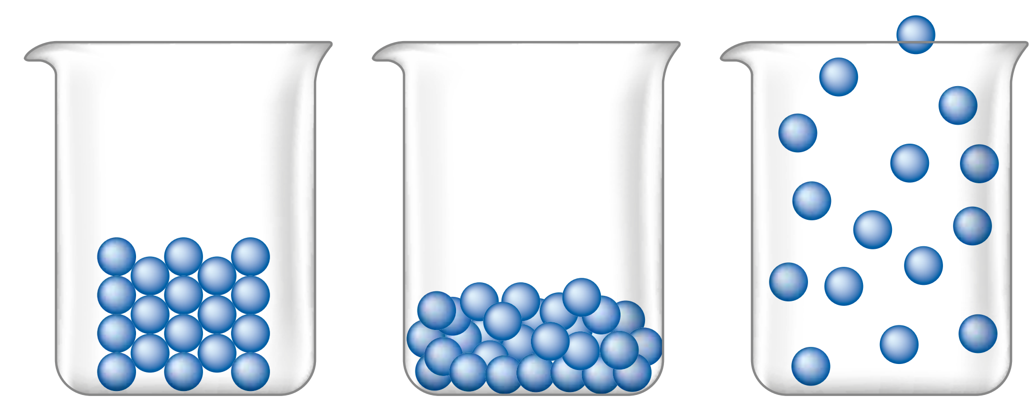

FIGURE 1 A simple diagram showing the three states of matter.

Solids

potential energy
stored energy found in the chemical bonds and nucleus of a substance

Particles in solids are held very closely together by strong bonding forces. This gives them **potential energy**. We call it microscopic potential energy (PE_{micro}) to distinguish it from the bulk, or macroscopic, potential energy you would have learnt about in Year 10 when you held a ball in the air ready to drop and time its fall. The strong bonding forces make solids

kinetic energy
the energy resulting from the movement of an object. When associated with temperature, kinetic energy is associated with the motion of particles in a substance

particles
a minute portion of matter. When associated with the kinetic model they are mainly atoms and molecules

very difficult to break apart. The particles don't move around from place to place but simply vibrate in their spot. This vibration means they have **kinetic energy** (also known as microscopic kinetic energy (KE_{micro})) as well.

Liquids

Particles in liquids are quite close, but the bonding forces between the particles is not as strong as in solids so they can slide past one another. Thus, they still have a fair amount of microscopic potential energy. Because the particles can move from place to place, we say they have translational motion (Greek *trans* = 'across', *lato* = 'to carry'). This gives them more kinetic energy. They can also have rotational motion, which means they can spin on their own axis. So long as they are not monatomic (single atoms like helium), they will have some rotational kinetic energy – but only a small amount. Water (H_2O) and ethanol (CH_3CH_2OH) are common laboratory examples of molecules with translational and rotational kinetic energy.

Can you compress a liquid? The answer is yes. You can compress liquids, even water, or almost any material. However, it requires a great deal of pressure to accomplish a little compression. For that reason, liquids and solids are sometimes referred to as being incompressible.

Gases

Particles in gases move around very quickly with a lot of space between them. The particles bounce off each. The intermolecular forces are quite weak, so the particles have little extra potential energy. But because they move at high speeds and rotate, they have considerable translational energy as well as the existing vibrational and rotational energy. Monatomic gases such as helium (He) of course don't have rotational energy – just translational.

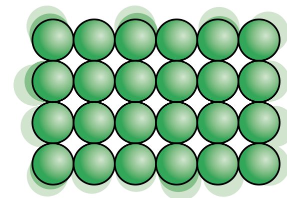
FIGURE 2 Particles in a solid are close together but can't move around. The arrangement is called a 'lattice'. Solids keep their own volume and shape when placed in a container.

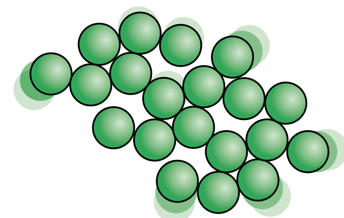
FIGURE 3 Particles in a liquid are close together and can move around. Liquids keep their own volume but take on the shape of the container they are placed in.

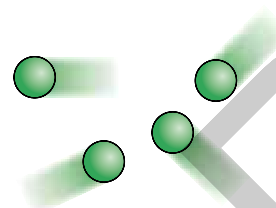
FIGURE 4 Particles in a gas are far apart and can easily move around. Gases take on the volume and shape of the container they are placed in.

Energy in the states of matter

If you have a solid, such as ice, you can add heat energy and it changes phase to become water. If you add more heat energy, it changes phase to become steam. That means steam has more energy than water, which has more energy than ice.

Kinetic theory summary

The kinetic molecular theory of matter accounts for the properties of matter in its three different phases. A simple statement of the model is:

- Matter is made up of particles that are constantly moving.

As a consequence of this, we can also say:

- Matter is made up of small particles (atoms or molecules) that are in constant random motion.
- There are large spaces between particles. The potential energy is related to the separation distance.
  - In a gas, the separation distance between particles is very large in comparison to their size so there are no attractive or repulsive forces between them.
  - In a liquid, the particles are still far apart but they are close enough that the attractive forces pull them together.
  - In a solid, the particles are so close that the forces of attraction confine the particles to a particular shape.
- Particles have energy. The temperature of a substance is a measure of the average kinetic energy of the particles.
- Collisions between particles are perfectly elastic ('elastic' means they do not lose kinetic energy when they collide).

	Solids	Liquids	Gases
Volume	keep own volume	keep own volume	take volume of container
Shape	keep own shape	take shape of container	take shape of container

TABLE 1 Summary of physical properties of states of matter

CHECK YOUR LEARNING 1.2

Describe and explain

1 Identify the main assumptions of the kinetic particle model.

2 Explain how the kinetic energy of a substance changes as it goes from a solid to a liquid to a gas. (You learnt about kinetic energy in Year 10.)

Apply, analyse and interpret

3 Deduce the microscopic nature of solids and liquids given that they can't be compressed very much. It takes large forces to compress them even slightly.

4 Derive a conclusion about the microscopic nature of gases given that they are very compressible compared with solids and liquids.

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» Suggested practical worksheet
1.2 Heating water on a hotplate – Graphing and analysing data

1.3 Temperature and kinetic energy

KEY IDEAS

In this section, you will learn about:

+ macroscopic energy and microscopic energy
+ internal energy.

macroscopic energy big or bulk forms of energy not at an atomic scale

microscopic energy energy of the particles that make up a substance including microscopic kinetic energy from the motion of particles and the microscopic potential energy of the chemical bonds and nucleus

chemical energy microscopic potential energy contained in the bonds within and between particles

nuclear energy microscopic potential energy contained within the nucleus of an atom

As well as kinetic and potential energy, there are two more energy terms that are important. It is essential that you know what they are and how they are different.

As mentioned before, objects can be considered to have their energy as two types: **macroscopic energy** and **microscopic energy**. Macroscopic energy is the sort of energy you dealt with in Year 10. When you throw a stone off a cliff, you would have said that the rock has gravitational potential energy $(E_P = mgh)$ and kinetic energy $\left(E_K = \frac{1}{2}mv^2\right)$. These are macroscopic (big or bulk) forms of energy. But we have also been talking about the energy of the particles that make up the object. This is called its microscopic energy. The distinction between macroscopic and microscopic energy is important.

All objects contain particles such as atoms or molecules and it is the motion of these particles that makes up the microscopic energy of the object. This motion can be vibrational kinetic energy, as in solids, or rotational and translational kinetic energy, as in fluids (liquids and gases). The particles of matter also possess many forms of microscopic potential energy in the chemical bonds (covalent, ionic and metallic) that hold particles together. This is called **chemical energy**. There is also energy stored in the nucleus of the atoms. This is called **nuclear energy**.

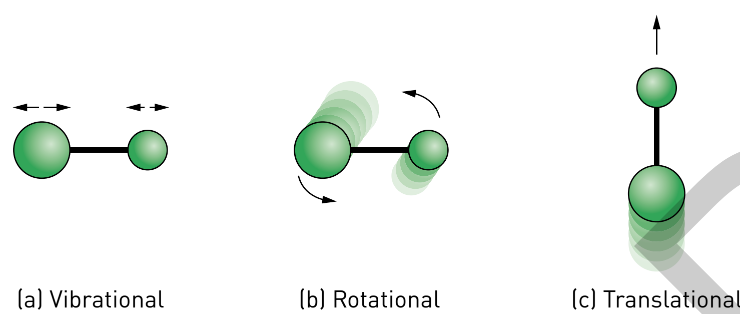

FIGURE 1 Three types of motion in molecules

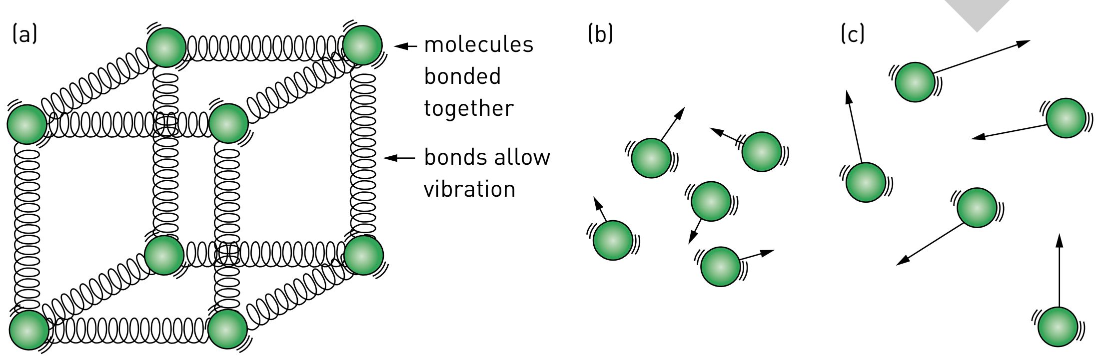

FIGURE 2 Main types of motion in each of the three states of matter: (a) vibrational motion in a solid; (b) translational motion in a liquid (plus some vibration and rotation); (c) translational motion in a gas (plus some vibration and rotation). There is also the chemical bond energy and nuclear energy inside the molecules.

Macroscopic energy

Consider a student throwing a ball (Figure 3) What energy does the ball possess?

You would say the ball has kinetic energy (KE or E_K) because of its motion from being thrown. This is equal to $\frac{1}{2}mv^2$, which means that as the object's velocity increases, its macroscopic kinetic energy increases. There is also gravitational potential energy (GPE or E_P) due to the ball's height above the ground (GPE = mgh). Macroscopic energy is defined as being due to the motion (velocity) or location (height) in a gravitational, electromagnetic or electrostatic field.

Macroscopic energy is the sum of these two forms of energy:

$$E_{\text{macro}} = E_{K(\text{macro})} + E_{P(\text{macro})}$$

But is that all the energy the ball possesses?

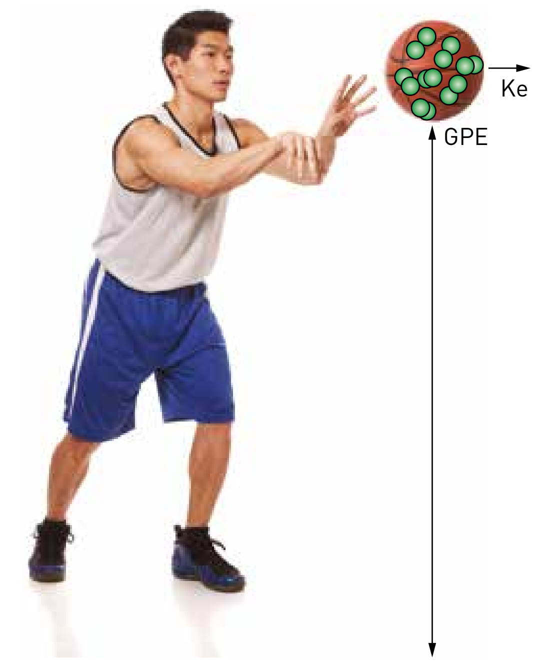

FIGURE 3 The energy contained in a ball in flight due to its motion (KE) and height (GPE), but note the gas molecules shown inside the ball.

Microscopic energy

Let's think about the situation if the motion of the gas particles inside the ball are considered. These particles could be the atoms, molecules, electrons or other particles that make up a substance. The total microscopic energy, E_{micro}, is made up of microscopic kinetic and microscopic potential energy.

$$E_{\text{micro}} = E_{K(\text{micro})} + E_{P(\text{micro})}$$

The $E_{K(\text{micro})}$ is made up of the microscopic kinetic energy due to translation, rotation and vibrations. The $E_{P(\text{micro})}$ is the microscopic potential energy of the bonds between particles in the substance, plus the binding of atoms by chemical bonds (E_{chem}). These bonds are broken and reformed during chemical reactions such as combustion. We have to also add in the microscopic nuclear energy (E_{nuclear}) contained inside the nucleus.

Internal energy

internal energy the total (microscopic) potential energy and (microscopic) kinetic energy of the particles in a system

thermal energy the internal energy present in a system due to its temperature (not including nuclear energy)

We can give this microscopic energy another name: **internal energy**.

Internal energy, U, is the total microscopic kinetic and microscopic potential energy of the particles in a system.

$$\text{Internal energy} = \text{microscopic kinetic energy} + \text{microscopic potential energy}$$

$$U = E_{K(\text{micro})} + E_{P(\text{micro})}$$

In thermal physics we are not concerned so much with the chemical and nuclear potential energy as they are not considered to change in the contexts we are dealing with. The energy in the chemical bonds and in the nucleus doesn't change for normal heating and cooling where no chemical reactions take place, so if we leave out these forms of energy we have **thermal energy**, E_{th}. For senior physics we use the terms 'thermal energy' and 'internal energy' interchangeably. This is because we are not interested in the total internal energy or total thermal energy, only a change in them.

It is nearly impossible to sum up all the forces that contribute to internal energy. We can't measure internal energy directly, so instead we measure the change in internal energy because this is the same as the change in thermal energy. Because the nuclear and chemical bond energy doesn't change for normal heating and cooling, we can say:

Change in internal energy of a system equals the change in thermal energy

$$\Delta U = \Delta E_{th}$$

The *exact* split of internal or thermal energy into microscopic kinetic and microscopic potential energy is outside the scope of these chapters.

In summary, the total energy of the system (the ball) is the sum of the energy of the ball due to the macroscopic energy and microscopic energy:

$$E_{sys} = E_{macro} + E_{micro}$$

$$E_{sys} = E_{K(macro)} + E_{P(macro)} + E_{K(micro)} + E_{P(micro)}$$

	Macroscopic energy		Microscopic energy		
	E_K	E_P	E_K	E_P	E_P
Type	energy due to movement (KE)	gravity, electric fields, magnetic fields	vibrational, rotational, translational energy of particles	forces between the particles in the stretched bonds	chemical and nuclear bonds (E_{chem}) ($E_{nuclear}$)
System energy, E_{sys}	✓	✓	✓	✓	✓
Internal energy, U			✓	✓	✓
Thermal energy, E_{th}			✓	✓	
Changes during heating and cooling	stationary, and doesn't change		the split between these varies, and is uncertain		doesn't change

TABLE 1 The forms of energy that make up total (or 'system') energy E_{sys}.

FIGURE 4 This netball has both kinetic energy from its motion and gravitational potential energy from its height above the ground.

You may wonder why internal energy was given the symbol U. In 1850, German physicist Rudolf Clausius was looking for a term to describe a previously undefined quantity related to the effect of heat on particles that was a function of velocity (v) and time (t). The letter 'U' was in between and it must have seemed logical. It doesn't stand for anything in real life.

The other factor we are not going to worry about is macroscopic energy. We consider the objects to be stationary, and in stationary systems there is no change in macroscopic energy. That means the change in energy of the whole system is due purely to change in internal energy:

$$\Delta E_{sys} = \Delta U$$

We also learnt that thermal energy is associated with temperature. That is, more thermal energy means a higher temperature, and vice versa.

Summary

- **Internal energy, U, is the total microscopic kinetic energy, $E_{K(micro)}$, and microscopic potential energy, $E_{P(micro)}$, of the particles in a system.** It does not include macroscopic energy.

$$U = E_{K(micro)} + E_{P(micro)}$$

- **Thermal energy, E_{th}, is the total kinetic and potential energy of the moving atoms and stretched bonds inside an object.** It does not include chemical or nuclear potential energy in the bonds.

$$E_{th} = E_{K(micro)} + E_{P(micro,\ excluding\ bond\ energy)}$$

- Thermal energy can also be regarded as that portion of internal energy that changes when the temperature of the system changes.
- Kinetic energy, E_K, is the energy associated with the motion of the particles in a system.

Study tip

It is important to be able to summarise and distinguish internal energy, thermal energy and kinetic energy. The statements provided here are a good start.

CHECK YOUR LEARNING 1.3

Describe and explain

1 a State the name given to the internal energy of a substance.

  b Name the form(s) of energy this involves.

2 Explain the difference between macroscopic and microscopic energy.

3 Describe the difference between thermal and internal energy.

4 Explain how heat, thermal energy and internal energy are related.

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1.4 Kinetic energy and temperature

KEY IDEAS

In this section, you will learn about:

+ the relationship between kinetic energy and temperature
+ the nature of elastic collisions.

When you heat up a substance, the average kinetic energy of the particles increases (so long as there is no phase change). For instance, if you heat 100 mL and 200 mL of water in beakers on a hotplate, the particles get faster and faster and their kinetic energy increases. The larger volume needs more heat to make it reach 100°C and boil than the smaller volume does. But when the water in each beaker boils, the average kinetic energies of their molecules are the same. We can say:

temperature the degree or intensity of heat present in a substance or object, especially as expressed according to a comparative scale, e.g. the Celsius temperature scale

Temperature is a measure of the average kinetic energy of the particles in a system.

Heating and change in thermal energy

Recall that thermal energy is made up of kinetic and potential energy. So, if the kinetic energy of particles in substance increases, so does its thermal energy (and, of course, its internal energy). Heating is the term used when some of the thermal energy is transferred from hot objects to cold objects, as in the case of a hot spoon being placed in cool water. We can thus define **heat as the transfer of thermal energy** in this heating process. A common misconception is that heat and temperature are the same, which is not the case. In common use it seems the same – you often hear 'turn up the heat' when referring to a room heater, when 'turn up the temperature' is meant. Heat is the *process* of transferring thermal energy in a system, whereas temperature is a *property* of the system.

A **change in temperature** is due to the addition or removal of energy from a system.

Let's consider the motion of particles in gases some more.

FIGURE 1 Perfume molecules evaporate and travel quickly because they are a gas. The hotter they are, the faster they travel.

A student at the back of the laboratory sprayed some deodorant in the air and within a few minutes it could be smelt out the front of the lab 8 metres away. Molecules of the perfume had travelled the 8 metres in about a minute. Does that mean that molecules of perfume vapour (gas) must have a speed of 8 metres per minute? Not necessarily – they would have taken a zigzag path to get there or could have been transported in bulk by a breeze as well. The gas particles actually move at something like a few 100 metres per second, but they don't go far before colliding with each other and the air about them. They collide about 6000 times per second and travel a long, long distance to get to the front of the room. So, we can say that gas particles are moving. They can vibrate, rotate and go from one place to another. In other words, the gas particles can have kinetic energy (Greek *kinema* = 'motion'). As you heat up a gas, the speed of the particles, and hence their kinetic energy, increases. This is shown by graph in Figure 2.

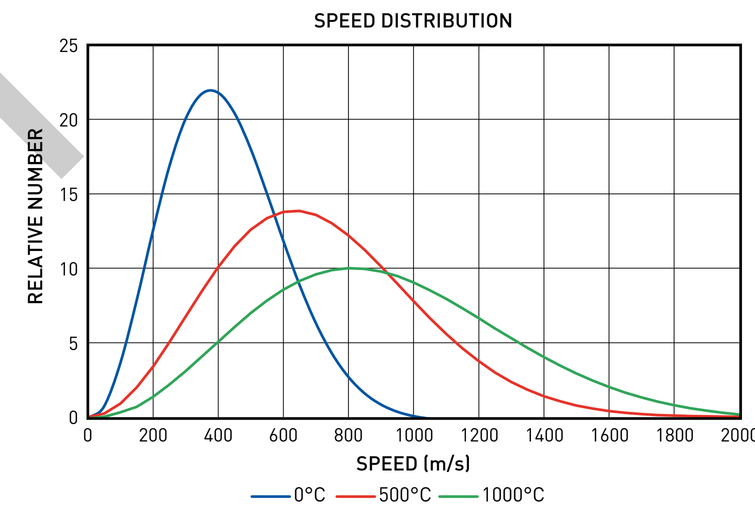

FIGURE 2 The speed of oxygen molecules at different temperatures. The most common speed is shown by the peak of each line. At 0°C (blue), the most common speed for oxygen is 400 m s^{-1}.

It would be impossible to measure the motion of all the particles within a substance because of the number of particles and the great variation in speeds of the particles. Figure 2 indicates the variation of molecular speeds of oxygen gas, O_2, at various temperatures. However, at any one moment in time there will be some molecules that are moving faster and will have more kinetic energy, and some that are moving slower and have less kinetic energy. When these molecules collide, they do not lose energy but tend to swap it. If a fast and a slow molecule collide, they bounce off each other and the fast one becomes slow, and the slow one becomes fast.

As objects gain heat and become hotter, the particles move faster. At a temperature of 500°C, the most common speed for oxygen molecules is 650 m s^{-1} and at 1000°C it is 800 m s^{-1}.

CHALLENGE 1.4A

Air on your skin

Imagine a 1 cm square on your skin. Every second there are 10^{22} 'blows' from air molecules. Can you detect it? If you can't, state some reasons why you can't feel these blows. If the blows stopped, predict what you would feel.

Kinetic energy and temperature relationship

In the past you learnt that kinetic energy (KE) relates to the mass and speed of an object. You learnt the formula KE $= \frac{1}{2}mv^2$. That is, the kinetic energy is the product of the mass and velocity squared all divided by two. For example, a 3 kg block moving at 10 m s^{-1} has a KE of $\frac{1}{2} \times 3 \times 10^2 = 150$ joules (150 J). This is said to be the object's macroscopic kinetic energy. However, in this section we are concerned with the particles within the object, such as the microscopic gas particles inside a balloon. As the temperature rises, the average speed of gas molecules inside the balloon rises and thus the average kinetic energy of the gas rises.

We can say that **kinetic energy is directly related to the temperature of the system.** Kinetic energy of gas particles is shown by the formula:

$$E_K = \frac{3}{2}\,kT$$

E_K = average kinetic energy per molecule of gas (J)

k = Boltzmann's constant (1.38×10^{-23} J K^{-1})

T = temperature in kelvin (K). To convert from Celsius (°C), simply add 273 (you will see why later, but for now just do the conversion).

This formula implies that, at a given temperature, all gas molecules – no matter what their mass – have the same average kinetic energy. From Year 10 you know that KE is also equal to $\frac{1}{2}mv^2$. We can put these two equations together to give:

$$E_K = \frac{3}{2}kT = \frac{1}{2}mv^2$$

WORKED EXAMPLE 1.4

Calculate the average kinetic energy of the air particles in a laboratory at 22°C.

Solution

The average translational kinetic energy of a molecule of a gas can be found using the formula:

$$E_K = \frac{3}{2}kT$$
$$= \frac{3}{2} \times 1.38 \times 10^{-23} \times (22 + 273)$$
$$= 6.11 \times 10^{-21}\ \text{J}$$

CHALLENGE 1.4B

Adiabatic compression

Space capsules get hot when they re-enter the Earth's atmosphere. This is usually said to be because of the friction between the metal and the air, but this is wrong! Space capsules are heated as they plough into the atmosphere and compress the air ahead of them. Have you ever pumped up a bicycle tyre and discovered that the pump and the tyre have become hot? The same effect causes spacecraft and supersonic aircraft to heat up as they compress the air at their leading edges. It is called 'adiabatic compression'. Design an experiment to show that the object becoming hot it is not from air friction.

MANDATORY PRACTICAL
1.4 Factors affecting the temperature of water being heated up
Go to page xxx »

Temperature and thermal energy

An electric kettle is quite a simple device. The longer you leave it turned on, the higher the temperature becomes (until it boils). That seems logical. A kettle is also quicker to heat up the less water there is in it. We could confidently say:

- the temperature increases as more thermal energy is added; or $\Delta T \propto$ thermal energy (Q)
- the temperature increase is greater with less mass of water; or $\Delta T \propto \frac{1}{\text{mass}}$.

These could be combined to say $\Delta T \propto \frac{Q}{m}$, or:

$$Q = mc\Delta T$$

where c is a constant of proportionality known as 'specific heat capacity' (which we will look at more in the next chapter).

Try Practical 1.4 to see if this proportional relationship between heat and temperature change holds experimentally.

CHECK YOUR LEARNING 1.4

Describe and explain

1 Express the meaning of temperature in terms of kinetic energy.

2 Calculate whether a nitrogen atom travelling at 400 m s^{-1}, means it will take $\frac{1}{4}$ s to travel the 100 m from one end of the school oval to the other.

Apply, analyse and interpret

3 Propose why nitrogen doesn't settle out near the floor and oxygen up near the ceiling given that it is made up mostly of nitrogen and oxygen, and that nitrogen is lighter than oxygen.

4 Determine at 1200°C, the average kinetic energies of:

a argon atoms?

b nitrogen molecules?

5 Deduce the temperature of neon atoms given that the average KE was found to be 1.2×10^{-20} J.

6 Consider that if you could suddenly increase the speed of every molecule in a gas by a factor of 2 the temperature of the gas would increase by a factor of 2, $\sqrt{2}$ or 2^2?

Investigate, evaluate and communicate

7 Evaluate the claims 'eating ice helps you lose weight' and that 'ice has negative joules' based on the idea that when you eat ice cubes, your body uses up energy to melt them and warm them up to body temperature.

Check your obook assess for these additional resources and more:

» Student book questions
1.4 Check your learning

» Video tutorial
Newton's Cradle

» Video tutorial
Graphing, linearising, adding trendlines and producing custom error bars

» Mandatory practical worksheet
1.4 Factors affecting the temperature of water being heated up

1.5 Measuring temperature

KEY IDEAS

In this section, you will learn about:

+ the Celsius, Fahrenheit and Kelvin scales as measures of temperature
+ how to convert between measurement scales.

In Section 1.4 you saw that **temperature is defined as a measure of the average kinetic energy of the particles within a system**. By 'system' we mean an isolated group of particles such as in a balloon, an ice block or beaker of water. The relationship is stated as $E_K = \frac{3}{2}kT$ for gases. There is no need to memorise this formula, but the question remains: 'how do we measure temperature and what units are used?' People also ask why does Australia use Celsius for temperature, but the United States uses Fahrenheit?

Measuring temperature requires the use of some property of a substance that changes proportionally with increase in temperature. Most temperature-measuring instruments use the property of expansion and contraction. In schools, the alcohol-in-glass thermometer is most common, whereas the mercury-in-glass is quite common in industry and research. Thermometers are calibrated to indicate the temperature. As temperature increases, the alcohol or mercury expands up a fine tube in the glass thermometer. The markings on the thermometer depend on the scale used (see Figure 1.)

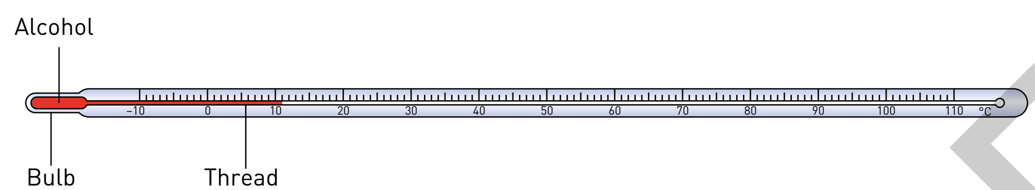

FIGURE 1 The liquid-in-glass thermometer. This one has alcohol, with a red dye, which expands more rapidly than the glass containing it. When the thermometer's temperature increases, the liquid from the bulb is forced into the narrow tube, producing a large change in the length of the column for a small change in temperature. Sometimes mercury is used as the liquid as it is suitable over a much larger range of temperatures (but dangerous if broken).

Throughout history, scientists have made up their own scales to measure temperature. Sir Isaac Newton made up a temperature scale where the freezing point of water was 0 degrees and normal body temperature was 12 degrees.

CHALLENGE 1.5

Cooling cannonballs

In 1780, French physicist Leclerc measured the rate of cooling of a very hot iron cannonball. Thermometers didn't exist, so he asked some women with soft hands to estimate the temperature. List three advantages and three disadvantages of this method.

Fahrenheit scale

A German physicist, Gabriel Fahrenheit (1686–1736), developed a liquid-in-glass thermometer and a temperature scale (now known as the **Fahrenheit scale**) that took the freezing point of an ice and salt mixture to be 0°F and his body temperature as 100°F. He marked those levels on his thermometer and divided the scale into 100 parts for each degree. The choices of his body temperature for 100°F and the freezing temperature of salt water for 0°F were unfortunate. Fahrenheit's metabolism was higher than most people, so 100°F for him resulted in 98.6°F as the body temperature for the average person.

Fahrenheit scale a temperature scale that takes the temperature at which water freezes into ice as 32°F, and the boiling point of water as 212°F

Fahrenheit designated the freezing temperature of a brine solution made from equal parts of ice and salt as 0°F. But that is certainly not the coldest temperature you can experience in winter weather. It also makes the freezing point of pure water an awkward 32°F. Since ocean water is not saturated with salt, it freezes at 28°F. What a mess. No wonder most countries got rid of the Fahrenheit scale!

Although the Fahrenheit scale is no longer used in Australia, is still used in several other countries such as the United States, Burma, Liberia, Bahamas, Belize, Palau and the Cayman Islands. The Fahrenheit scale is now usually defined by two fixed points (as defined at sea level and standard atmospheric pressure): the temperature at which water freezes into ice is 32°F, and the boiling point of water is 212°F. These defined points give the scale a separation of 180°F.

The conversion between Fahrenheit and Celsius is:

$$°\mathrm{C} = (°\mathrm{F} - 32) \times \frac{5}{9}$$

Celsius scale

An easier decimal temperature scale was invented by a Swedish astronomer, Anders Celsius (1701–44). On the **Celsius scale** (also called the centigrade scale), the freezing point of pure water is 0°C and the boiling point is 100°C. Interestingly, Celsius originally took the freezing point to be 100°C and boiling point to be 0°C, but this was changed in the first year. The Celsius scale is the main scale used in measuring body temperature and in all scientific work (see Figure 2). It is the common scale throughout most of the world.

Celsius scale a temperature scale that takes absolute zero as −273.16°C and the triple point of water (where solid, liquid and gas exist together), as 0.01°C

Kelvin scale

The Fahrenheit and Celsius scales are relative scales – that is, zero degrees on either scale does not mean that this is the lowest temperature obtainable. Since temperature is a measure of the average kinetic energy of the particles, 0°C does not mean that all particle motion has stopped. So, at what temperature does all motion stop? This point would be the true limit of coldness and would produce an absolute zero temperature. Scottish professor William Thomson (Lord Kelvin, 1824–1907) suggested this temperature was −273.15°C.

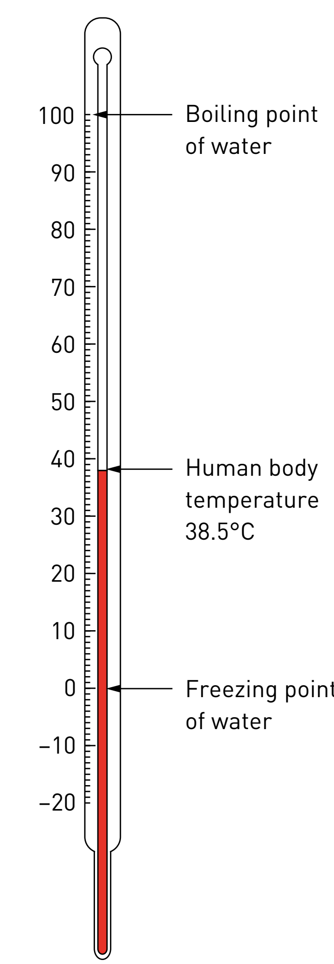

FIGURE 2 A Celsius thermometer is commonly used in the laboratory and in the home.

absolute zero
the lowest temperature that is theoretically possible, at which the motion of particles which constitutes heat would be minimal. It is zero on the Kelvin scale

Kelvin scale
a temperature scale that takes absolute zero as 0 K and the triple point of water (where solid, liquid and gas exist together), as 273.16 K

When a sample of gas of constant volume is heated, its pressure varies with Celsius temperature. This is shown in Figure 3. Extrapolation of this graph suggests that, at –273.15°C, the pressure becomes zero and therefore all particle motion stops. This is because pressure is caused by particles colliding with the container walls – if there is no motion, there are no collisions and therefore no pressure. This point is called **absolute zero** on the **Kelvin scale** of temperature. However, one degree on the Kelvin scale is equal in magnitude to one degree on the Celsius scale.

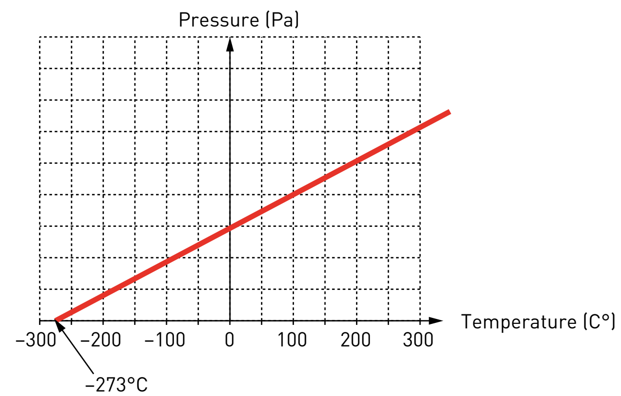

FIGURE 3 The relationship between temperature and pressure, and the establishment of absolute zero.

STUDY TIP

You might find it easier to remember the conversion from kelvin to Celsius as K = °C + 273.

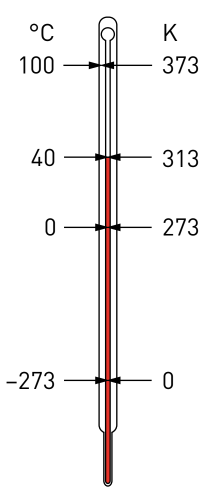

FIGURE 4 A comparison of temperature in degrees Celsius and kelvin

At 0 K, the kinetic energy of the particles is zero and all that is left is microscopic potential energy. However, in terms of quantum mechanics (which is beyond what we need to know here), there is said to be some residual potential energy in the particles. This is called ‘zero-point energy’. It is enough to say that, at 0 K, the system is in the lowest energy state rather than zero energy state.

Therefore, changing Celsius temperature to kelvin temperature simply requires the addition of 273 (to three significant figures) to the Celsius value.

$$\text{kelvin temperature} = \text{Celsius temperature} + 273$$
$$T_K = T_C + 273$$

Figure 4 shows a comparison between the two scales.

WORKED EXAMPLE 1.5A

Convert 50°C to kelvin.

Solution

$T_K = T_C + 273$
$= 50°C + 273$
$= 323\ K$

WORKED EXAMPLE 1.5B

Convert 486 K to °C.

Solution

$T_K = T_C + 273$
$486 = T_C + 273$
$486 - 273 = T_C$
$T_C = 213°C$

Which scale is best?

The Kelvin and Celsius scales are defined using absolute zero (0 K) and the triple point of water (where solid, liquid and gas exist together, namely 273.16 K and 0.01°C) as their operational definition for the scale. However, it is impractical to use this definition at temperatures that are very different from the triple point of water. Accordingly, numerous defined points are now used, all of which are based on various thermodynamic equilibrium states of 14 pure chemical elements and one compound (water). Most of the defined points are based on a phase transition; specifically, the melting/freezing point of a pure chemical element. Other defining points are the triple point of hydrogen (–259.3467°C) and the freezing point of aluminium (660.323°C).

Fahrenheit, on the other hand, is also defined by the freezing and boiling points of water but not to other extended points. The other benefit of Fahrenheit is that a Fahrenheit degree is only $\frac{10}{17}$ the size of the Celsius degree, which allows more precise communication of measurements without resorting to fractional degrees.

In this Australian text, we will use °C and K.

Person's name	Daniel Gabriel **Fahrenheit**	Anders **Celsius**	Lord **Kelvin** (William Thomson)
Name of scale	the Fahrenheit scale	the Celsius scale	the Kelvin scale
Unit symbol	F (e.g. 42°F)	C (e.g. 18°C)	K (e.g. 301 K)
Unit description	42 degrees Fahrenheit	18 degrees Celsius	301 kelvin (note the lowercase ‘k’)

TABLE 1 How to refer to each temperature scale correctly

CHECK YOUR LEARNING 1.5

Describe and explain

1 Define temperature.
2 Identify the lowest possible temperature on the Kelvin scale. Explain why is it called ‘absolute zero’?
3 Calculate the following temperatures in K:
 a 20°C b –150°C c 520°C
 d –72°C e –300°C.
4 Calculate the following temperatures in °C:
 a 50 K b 278 K
 c 1000 K d –50 K.
5 Identify the scale on overseas friend was using if he said his son had a temperature of 99 degrees.

Apply, analyse and interpret

6 Propose why the liquid in a thermometer rises as it heats up?
7 Deduce at what temperature °C and °F will be the same? Explain whether a kelvin temperature reading could ever be the same as a °C or °F reading?

Investigate, evaluate and communicate

8 Devise a formula for converting Fahrenheit temperatures to kelvin in case you go to the United States and want to convert to do this.

Check your obook assess for these additional resources and more:

» Student book questions
1.5 Check your learning

» Activity
Precision and accuracy of alcohol in a glass thermometer

» Weblink
tbc

» Weblink 2
tbc

SCIENCE AS A HUMAN ENDEAVOUR

1.6 The development of temperature scales

KEY IDEAS

In this section, you will learn about:

+ the human endeavour behind the development of temperature scales.

For a large part of human history there has been no formal distinction between the concepts of heat and temperature. People spoke of the degrees of hot or cold, but these degrees were not measured – except perhaps in a very rough way as when a physician put their hand on a patient's forehead and diagnosed 'fever heat'. Isaac Newton himself asked young women to place their hands on cooling cannonballs to give him a sense of the degree of hotness.

Over the past 500 years there have been numerous temperature scales developed. Some of these are outlined in the timeline shown. However, the development of temperature measurement does not stop here (as you will see in the next section).

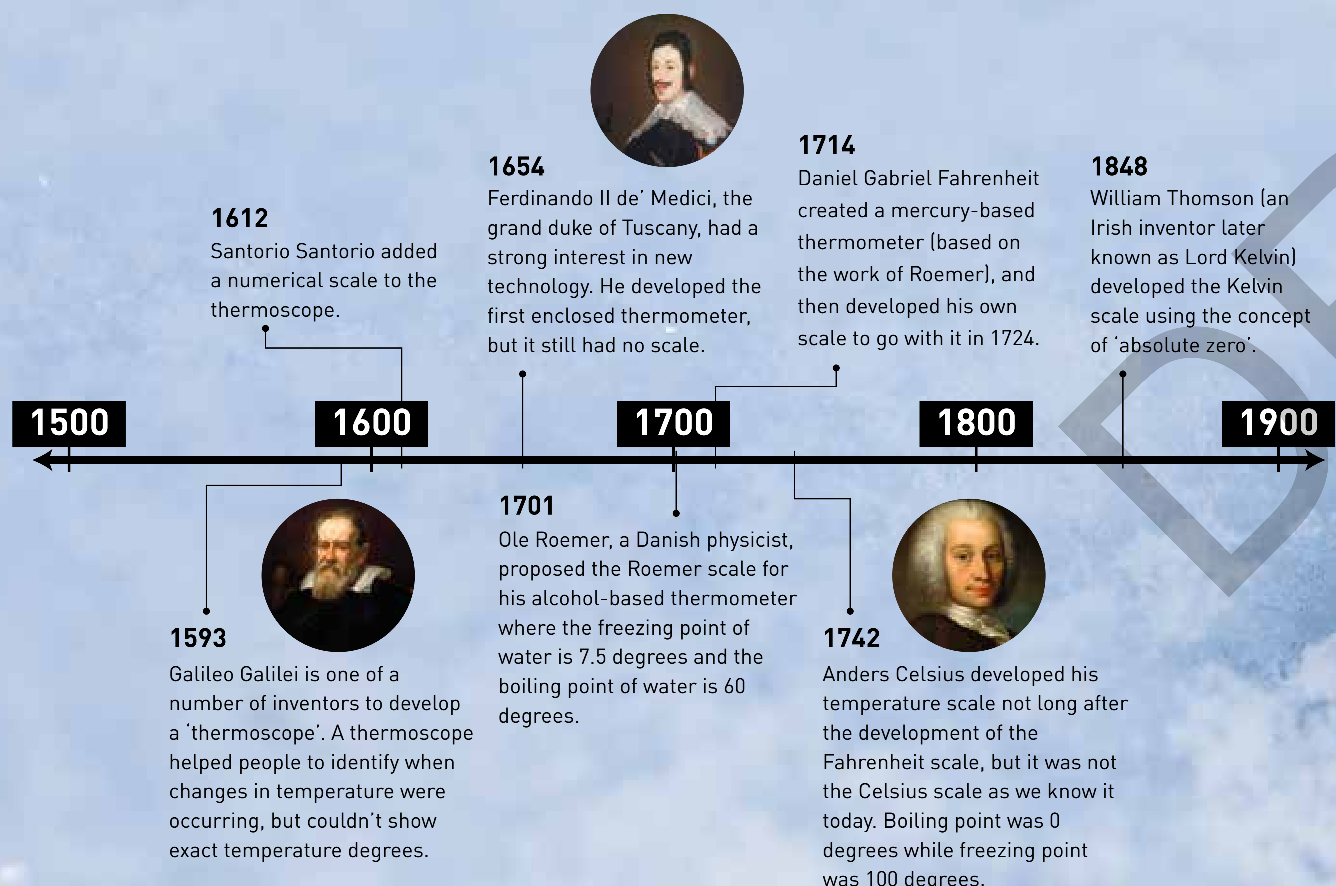

FIGURE 1 Timeline of the development of different temperature scales

There are two common definitions of temperature:

- temperature is a measure of the average kinetic energy of the particles within a sample of matter
- temperature is the reading on a thermometer.

So, how does a thermometer register the kinetic energy of the particles? If the particles have zero KE, then we can say the temperature is zero (kelvin). But what of other temperatures? The logic is simple. The theoretical basis for thermometers is the zeroth law of thermodynamics, which is illustrated as follows: Place a thermometer in substance A and when the substance and thermometer come to thermal equilibrium, take a reading. Then place the same thermometer in substance B and at equilibrium take a reading. If the reading is the same in both cases, then A and B are at the same temperature.

In simple terms, when two bodies have the same temperatures as a third body, then the two also have temperature equal to each other.

Thermometers tell us two things:

1 if an object has the same temperature as another object (zeroth law)

2 the direction that thermal energy will flow spontaneously (from high temperature to low) when two objects of different temperatures are brought in contact (second law).

CHECK YOUR LEARNING 1.6

Describe and explain

1 Specify the problem with temperature measurement before scales were invented.

2 Explain why the thermoscope would not have been a good measure of temperature.

Investigate, evaluate and communicate

3 Evaluate the comment: 'The three common temperature scales – Fahrenheit, Celsius and Kelvin – were developed in the order stated. It is sometimes claimed that each was an improvement on the previous scale' by:

a assessing this claim by analysing how and why these scales developed over time.

b discussing the factors that prompted their review.

4 Discuss what problems are associated with using the Fahrenheit scale given that the United States is one of the few countries in the world to still use it.

Check your obook assess for these additional resources and more:

» Student book questions
1.6 Check your learning

» Video tutorial
tbc

» Weblink
tbc

» Weblink 2
tbc

1.7 Other types of thermometers

KEY IDEAS

In this section, you will learn about:

+ alternative methods of measuring temperature.

Even though liquid-in-glass thermometers are the most widely used, they have their limitations. This is mainly due to the liquid freezing or boiling. Alcohol-in-glass thermometers can be used between –10°C and 110°C. Mercury-in-glass thermometers have an operating range of –40°C to 360°C. Glass is also fragile, and mercury is toxic to the body and the environment. The liquids are also uneven in their expansion – it varies a tiny amount with temperature.

Gas thermometers

Gas thermometers rely on the expansion of gas. Since change in temperature is proportional to the change in volume of a gas, the expansion of a gas can be calibrated to measure temperature.

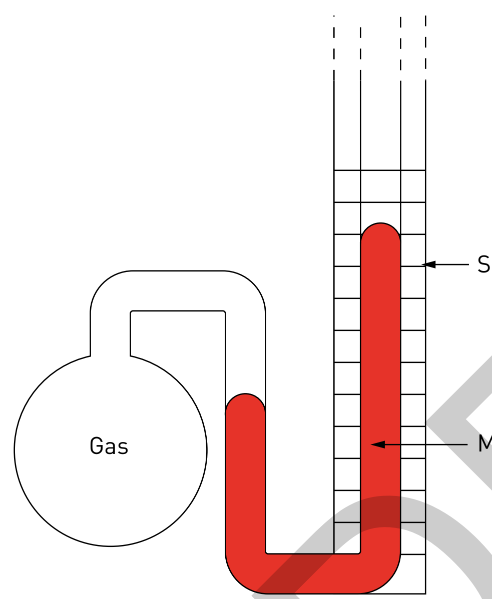

FIGURE 1 A constant volume gas thermometer relies on the relationship between temperature and pressure.

Resistance thermometers and thermocouples

Resistance thermometers, also known as resistance temperature detectors (RTDs), are sensors that utilise the properties of wires. Electric current in wires decreases as temperature rises, so the change in electric current of an RTD wire can be used to measure temperature. The RTD wire is a pure material that has an accurate resistance–temperature relationship (usually platinum, nickel or copper). As RTD components are very delicate, they often have a protective casing.

Thermocouples consist of two wires made of different metals. The wires are made into a loop that includes a voltmeter (see Figure 2). One end of the wire combination is kept at a reference temperature while the other end is used as a probe. When this probe is placed in a substance to be measured, the voltage produced is proportional to the difference in temperature between the two ends. Thermocouples can be used to measure temperature over a wide range. For example, the nickel–chromium alloy and nickel–aluminium alloy combination has a range of –270°C to 1260°C. Even the much simpler copper and constantan combination has a range of –270°C to 370°C.

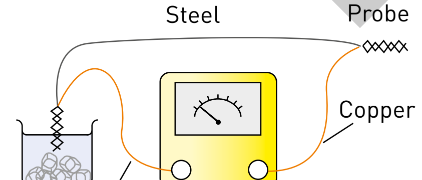

FIGURE 2 A thermocouple is a thermometer consisting of two dissimilar metals. The difference in the temperatures of the two ends produces a voltage. This can be calibrated to 'read' temperature.

Bimetallic strips

Bimetallic strips rely on the different expansion rates of two different metals. When heated, one metal expands more than the other. This causes bending and movement of a pointer across a scale. Bimetallic strips have a wide working range.

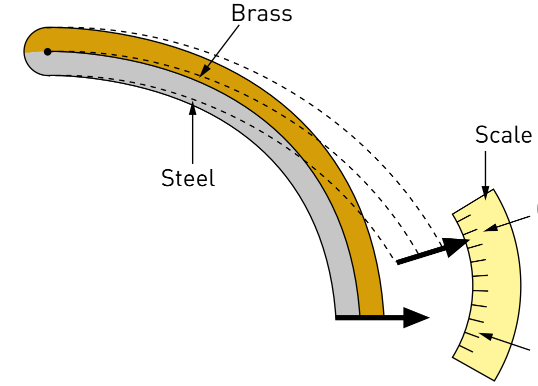

FIGURE 3 A bimetallic strip thermometer. The difference in expansion rates between the two different metals causes a pointer to move across a scale.

Liquid crystal thermometers

In **liquid crystal thermometers**, numbers on a scale are made of different crystalline chemicals. As temperature increases, these chemicals change their crystalline structure, which results in colour changes. Liquid crystal thermometers are not very accurate.

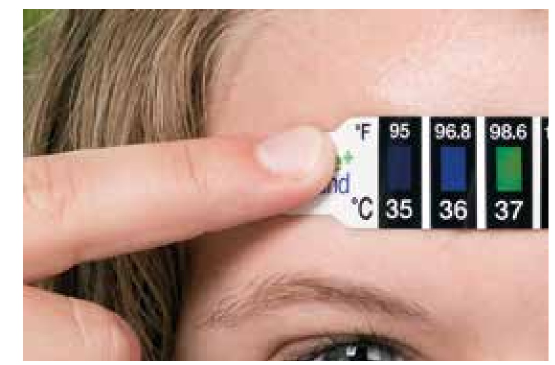

FIGURE 4 Liquid crystal thermometers are good for measuring body temperature. Each of the six squares on this plastic (liquid crystal) thermometer contains a film of a different heat-sensitive liquid crystal material. Below 35°C, all six squares are black. At 35°C, the first liquid crystal square changes colour. As the temperature rises, further crystals change colour.

Pyrometers

Pyrometers measure the radiation given off by objects. The characteristic of the radiation changes with temperature. Infrared pyrometers can measure temperature from –20°C to 1500°C. Body temperature is routinely monitored in clinical settings with infrared ear thermometers, which measure the infrared energy emitted from the patient's eardrum in a calibrated length of time. A short tube with a protective sleeve is inserted into the ear, and a shutter is opened to allow radiation from the tympanic membrane to fall on an infrared detector for 0.1 to 0.3 seconds. The device beeps when data collection is completed, and a readout of temperature is produced on a liquid crystal display.

FIGURE 5 An infrared pyrometer allows you to measure temperature without making physical contact. Normal skin temperature varies between 33°C and 37°C.

Thermistors

Thermistors are semiconductor devices that change their resistance with change in temperature. When these devices are heated, their resistance decreases and more current flows. The current is measured on an ammeter, which is calibrated to read temperature.

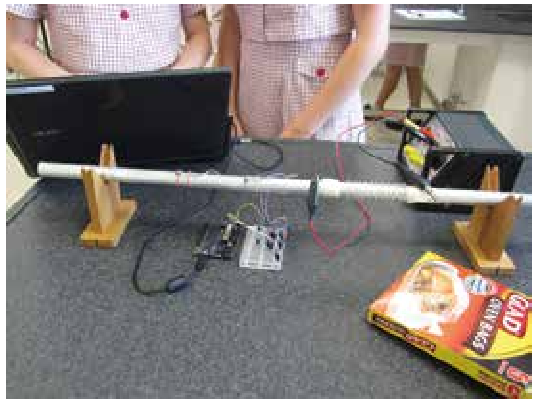

FIGURE 6 Three thermistors attached to a heated metal rod with rubber bands. Students were logging the temperature changes in the rod using an Arduino and thermistors. They could also have used a pyrometer (as in Figure 5).

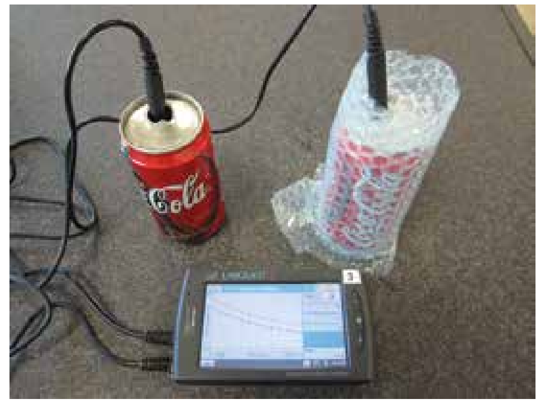

FIGURE 7 A stainless-steel temperature probe (as used in a science class) consists of a thermistor attached to a stainless-steel rod. It is being used here to measure the rate of cooling of water in an insulated can. Note the two graph lines on the screen.

CHECK YOUR LEARNING 1.7

Describe and explain

1 Identify and describe two methods of measuring heat that do not involve a liquid-in-glass thermometer.

2 Summarise why might someone choose to not use a liquid-in-glass thermometer.

Investigate, evaluate and communicate

3 Table 1 shows the effects of low body temperature.

Body temperature (°C)	Effect
37.0 ± 1	normal
35	shivering
34	slurred speech
33	hallucinations
32	shivering stops
30	unconsciousness
26	appears dead

TABLE 1 Effects of low body temperature

Death is defined as a failure to revive on rewarming above 32°C. When people freeze to death in cold water, it has been reported that they do not seem to be in pain as they die. They often seem relaxed. Deduce why there might be an absence of pain.

Check your obook assess for these additional resources and more:

- » Student book questions 1.7 Check your learning
- » Video tutorial Bimetallic strip
- » Weblink tbc
- » Weblink 2 tbc

1.8 Thermal expansion

KEY IDEAS

In this section, you will learn about:

- thermal expansion
- expansion of gases, solids and liquids.

thermal expansion the tendency of matter to change in shape, area, and volume in response to a change in temperature

One of the consequences of heating a substance is that it expands. You saw this with the liquid in the stem of a thermometer. **Thermal expansion** is due to the increased speed of the particles, or the increased vibrations within and between the particles themselves.

This can easily be shown for each of the three common states of matter: solids, liquids and gases.

Expansion of gases

Consider a conical flask with a balloon over the opening. When heated, the increased speed of the gas molecules means they have a bigger impact on the walls of the flask. The flask is rigid, so it can't move when the molecules strike – the molecules just bounce off. However, the rubber balloon at the top of the flask can stretch. If we apply a force, the rubber will stretch and grow larger. The impact from the molecules on the rubber applies such a force, and will be greater than the force of the atmosphere pushing back, so the balloon moves outwards.

The effects of heat on gases are easy to understand because of the limited effect particles of the gas have on one another (except in collisions). The addition of thermal energy affects the particles of the gas by making them move faster, and thus expanding the gas or increasing its pressure on its container. Does heating have the same effect on the particles of solids and liquids?

Expansion of solids

Think about the following questions:

- What causes the mercury in a thermometer to rise?
- Why do trains make the 'clickety–clack' sound when moving over railway lines?
- If you heat a steel ruler with a small hole in one end, does the hole get bigger or smaller?

With very few exceptions, all solids expand when they are heated and contract when they are cooled. What is the underlying cause of thermal expansion? Remember that an increase in temperature is a result of an increase in the kinetic energy of the individual atoms. In a solid, although the atoms or molecules are closely packed together (unlike in a gas), their kinetic energy (in the form of small, rapid vibrations) pushes neighbouring atoms or molecules apart from each other. This neighbour-to-neighbour pushing results in a slightly greater distance (on average) between neighbours, and adds up to a larger size for the whole body. For most substances under ordinary conditions there is no preferred direction, and an increase in temperature will increase the solid's size by a certain fraction in each dimension.

The reverse of heating is cooling, and cooling causes contraction. For example, cooling a 15.000 m length of aluminium from 60°C to 20°C will cause it to contract by 9 mm. This causes the clickety-clack of older train tracks, as expansion gaps of about 10 mm had to be left for the steel rail to expand into.

This expansion may not seem very much, but if the length is big enough and the temperature rise large enough, the expansion will be noticeable. For example, in the early 1800s, steam had just been introduced to power the factories. Steam pipes in the cotton mills were often over 130 m long. With temperature rises from a cold 10°C to 400°C, the increase in length was such that a carpenter's ruler could be used to measure it.

FIGURE 1 Expansion gap left between the old railway lines

FIGURE 2 Thermal expansion joints, such as these in the Auckland Harbour Bridge in New Zealand, allow bridges to change length without buckling.

Volume expansion

A solid has three length measurements: length, width and height. All three directions expand or contract, therefore the volume of a solid changes with temperature change. This can be an advantage as well as a disadvantage in everyday life.

- Gear wheels are fitted to axles using cold shrinking. The axle is cooled in liquid nitrogen and it contracts, which allows the gear wheel to fit on easily. When the axle warms up to normal temperature, it makes a very tight fit. Cold shrinking has the advantage that it won't warp or discolour the metals, or change its crystal composition and hence its properties.
- Telephone and electrical cables are hung loosely between poles to allow for contraction in cold weather conditions.
- Bimetallic strips that consist of two dissimilar metals of equal length are used in fire alarms (see Figure 3).

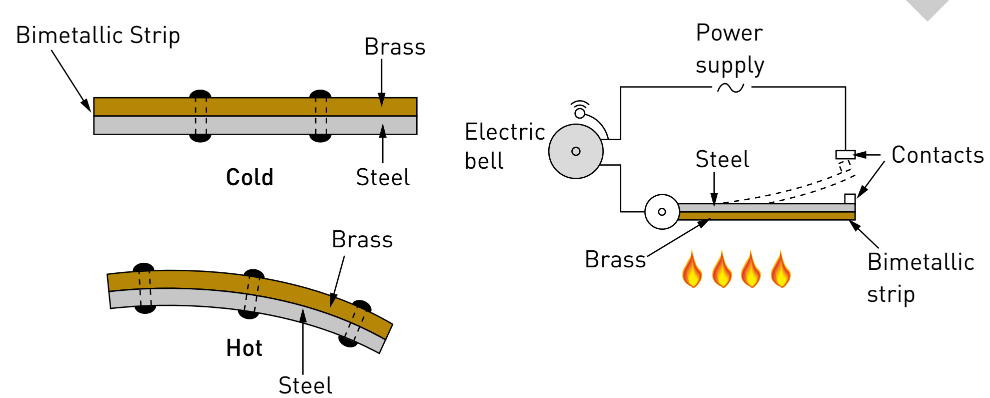

FIGURE 3 Bimetallic strip used in a fire alarm.

- Bridges and rail lines have expansion gaps to allow for expansion in hot conditions to stop buckling.
- Large buildings and concrete paths often have rubber expansion gaps that allow for the expansion of the concrete, to stop cracking.
- Fillings in teeth and the teeth themselves need to have similar coefficients of expansion. A mismatch may result in microleakage and wear problems.
- Crown glass shatters when you pour boiling water into it, but Pyrex does not.
- In aircraft manufacture, rivets are often cooled in dry ice before insertion and then allowed to expand to a tight fit.
- Pipes in refineries often include an expansion loop so that the pipe will not buckle as the temperature rises.

Expansion of liquids

As we have previously discussed, a very common device making use of the expansion of liquids is a thermometer.

As the temperature increases, the mercury or alcohol in the thermometer increases in volume and moves up the fine tube. Another example of the expansion of liquids is the explosion of a bottle filled with liquid when it is left in the hot sunlight.

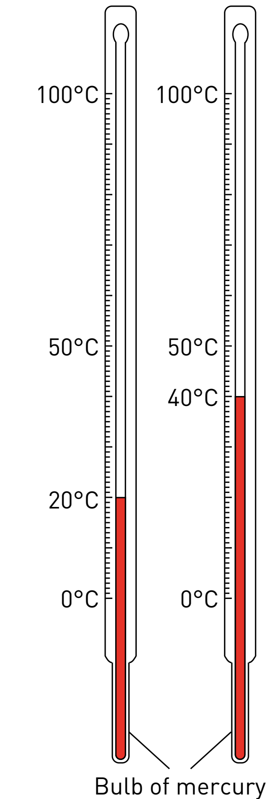

FIGURE 4 Expansion of mercury in a thermometer.

CHALLENGE 1.8B

When should you buy petrol?

Differences in the thermal expansion of materials can lead to interesting effects at the service station. Are you better off buying petrol from the service station on a hot day or a cold day? You would think that on a hot day the petrol has expanded and there would be fewer molecules in a litre. What do you think?

CHECK YOUR LEARNING 1.8

Describe and explain

1 Describe the two essential properties of a liquid used in a thermometer?

Apply, analyse and interpret

2 Propose why houses with steel roofs on a timber frame will creak when a cloud passes overhead on a hot summer's day and provide quantitative data to support your claim.

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CHAPTER 1

Review

Summary

- 1.1 Heat is energy in the process of being transferred from one place to another due to the temperature difference. It can be defined as the transfer of thermal energy.
- 1.2 The kinetic particle model of matter suggests that matter is made up of particles that are constantly moving.
- States of matter include solids, liquids and gases.
- 1.3 Objects can be considered to have their energy as two types: macroscopic energy and microscopic energy.
- Internal energy, *U*, is the total microscopic kinetic and microscopic potential energy of the particles in a system.
- Change in internal energy of a system equals the change in thermal energy.
- 1.4 Temperature is a measure of the average kinetic energy of the particles in a system.
- Kinetic energy is directly related to the temperature of the system.
- 1.8 The heating a substance causes it to expand due to the increased speed of the particles or the increased vibrations within and between the particles themselves.

Key terms

- absolute zero
- atom
- Celsius scale
- chemical energy
- energy
- Fahrenheit scale
- heat
- internal energy
- Kelvin scale
- kinetic energy
- kinetic particle model of matter
- macroscopic energy
- microscopic energy
- nuclear energy
- particle
- potential energy
- temperature
- thermal energy
- thermal expansion

Key formulas

Converting kelvin to Celsius	Kelvin temperature = Celsius temperature + 273 $T_K = T_C + 273$

Revision questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: ★ = low; ★★ = medium; ★★★ = high.

Multiple choice

1 Which of the following statements about the Kinetic Theory of gases is NOT true:
  - a All molecules move with the same speed
  - b Their average kinetic energy is directly proportional to the absolute temperature
  - c All molecules make elastic collisions with each other and the walls of the container
  - d The molecules travel in straight lines until they collide

2 When one end of a cold metal spoon is placed upright in a cup of hot coffee, the other end gets hotter. Which one of the following best describes what is happening?
  - a Warmer molecules will rise to the top
  - b The hot molecules produce thermal radiation that is then absorbed by the colder molecules.
  - c Higher-energy molecules hit lower-energy molecules, increasing their speed and therefore their temperature.
  - d Lower-energy molecules hit higher-energy molecules and the friction increases their temperature.

3 Three sealed flasks each containing 1 g of water, ice, and water vapour are at the same temperature. Which of the following is true about the internal energy of the substances?
  - a U water > U ice > U vapour
  - b U water = U ice = U vapour
  - c U water < U ice < U vapour
  - d U ice < U water < U vapour

4 A sealed container of air is kept at a constant temperature. What will happen to the speed of the molecules of air in the container as time passes?
  - a The molecules will all reach the same speed.
  - b Some molecules will speed up and others will slow down, but the average speed will be constant.
  - c The molecules will slow down.
  - d There will be no change.

5 A scientist is feeling sick and knows that if her temperature is a degree or more above 37.5 °C she should go home from work. But all she has is a thermometer graduated in kelvin. What temperature does the thermometer need to be?
  - a 194.5 *K*
  - b 310.5 *K*
  - c 311.5 *K*

Short answer

Describe and explain

★ 6 Define temperature, energy, heat.

★ 7 'You can't see water molecules vibrate, but if you added food colouring you could.' True or false? Explain.

★ 8 Describe three differences between solids, liquids and gases.

★ 9 Select the key phrase from each one of the main points to the kinetic theory.

★ 10 You can compress gases but not solids. Can you partially compress liquids? Explain.

★★ 11 Identify the limitations of a model for gas behaviour that uses a box full of bees.

★ 12 Describe an elastic collision and explain how it pertains to gases.

★ 13 Explain why you can smell if a gas tap has been left on when you walk into a laboratory, but you cannot smell the water spilt on the front bench.

★ 14 Evaluate the statement that heat and cold flow like liquids because heat seems to 'run' from hot to cold.

★ 15 Assess whether you can say coldness flows from the ice to the water when you put an ice cube in water.

★★ 16 Explain the main assumptions we make about gases regarding their collisions.

★ 17 Explain why it is good to have a common temperature scale around the world.

★ 18 Compare the thermal energy of a swimming pool at 30°C and a cup of coffee at 90 °C.

★ 19 Clarify if heat and temperature the same thing by giving an example of two objects that could contain the same heat (thermal) energy but at different temperatures.

★ 20 Describe how allowances are made for the expansion of concrete paths, and explain why it works.

★★ **21** A 100.00 m long steel water pipe was laid in the ground on a hot summer's day when the temperature was 25°C. A one metre long rod of steel is known to change length by 10 micrometres for every 1°C change in temperature. Calculate its new length if the ground temperature fell to –15°C. Note, $\mu = 10^{-6}$.

★★ **22** The Statue of Liberty is made of a steel frame 46.00 m high. It experiences cold January temperatures as low as −5 °C and once had a July summer temperature of 45°C. Calculate the difference in height between the two extremes. You know that 1.0 m of steel expands by 10 μm per 1°C rise in temperature.

★★ **23** A 1.00 cm cube of brass was weighed at 20°C and it was found to have a mass of 8.73 g. This gave a density of 8.73 g/cm³. The cube was then heated to 120°C. The linear expansion value for brass is 19 μm per °C for every 1.0 metre of length. Calculate:

- **a** the new length of each side
- **b** the new volume
- **c** the density at 120 °C

Apply, analyse and interpret

★ **24** Explore whether heating water from 20°C to 40°C really doubling the temperature?

★ **25** Determine the following temperatures in K:

- **a** 30°C **b** –120°C **c** 550°C
- **d** –92°C **e** –200°C

★ **26** Express the following Celsius temperatures in kelvin:

- **a** 290°C **b** –25°C **c** 59.2°C

★ **27** Express the following temperatures in °C:

- **a** 150 K **b** 378 K
- **c** 6000 K **d** –10 K

★ **28** Express the following kelvin temperatures in °C:

- **a** 69 K **b** 1376 K **c** 345.6 K

★★★ **29** Deduce whether this statement is true or false? 'When you double the kelvin temperature of a gas, you double the average speed of the molecules.'

★ **30** Deduce two reasons why a mercury-in-glass thermometer could not be used to measure the temperature of a pottery kiln when it is in use.

★ **31** Compare which is better: a thermocouple or an alcohol-in-glass thermometer.

★ **32** Judge the temperatures of the thermometers in Figure 1 to the nearest half-scale division.

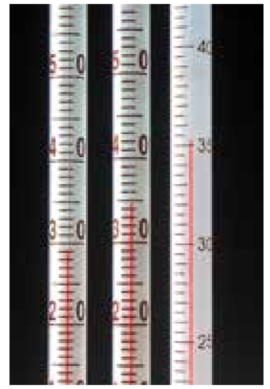

FIGURE 1

★★ **33** Determine fallacy in this claim. An advertisement for insulation said it would 'reduce roof temperatures from 60°C to 30°C, and that's a 50% reduction'.

★★ **34** Devise a graph, using a spreadsheet, showing the relationship between kelvin and Celsius temperatures. Place degrees Celsius on the horizontal axis. Write the equation for the line in the form $y = mx + c$.

★★ **35** Predict what will happen when a trimetallic strip of metal, prepared using three metals, as shown in Figure 2, is heated. The coefficient of linear expansion value for brass is 19×10^{-6} °C⁻¹, and for iron is 12×10^{-6} °C⁻¹, which means brass expands more than iron for the same temperature increase.

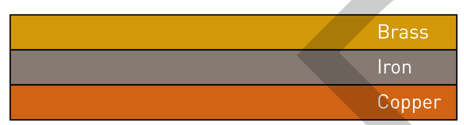

Figure 2

★★ **36** Explain which one of the graphs in Figure 1 best shows the relationship between kinetic energy of a gas molecule and its temperature (horizontal axis).

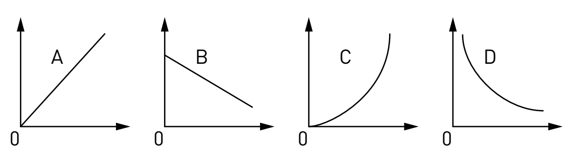

FIGURE 1

★ **37** Consider in terms of the particle model why metals expand when heated.

★ **38** Consider why some metals expand more than others – for instance steel expands more than brass for the same temperature rise.

★ **39** Deduce whether the claim that 'Liquids expand when heated, except for water, which shrinks' is true.

★ **40** Using kinetic theory consider why if you run hot water over a tight metal lid on a glass jar before trying to open it, it can be easier to open.

★ **41** Consider why some materials shrink with increasing temperature given that liquids and solids expand with increasing temperature because the kinetic energy of a body's atoms and molecules increases.

★★ **42** Assess the questions below based on the fact that water expands by about 10% when it freezes and produces sharp ice crystals.

- **a** Why is it that a quarter of biological cells burst when animal or plant material is frozen?
- **b** What are the implications of this cell damage in relation to preserving human bodies by freezing so that they can be thawed at some future date when it is hoped that all diseases are curable?

★ **43** Propose a reason for this process. To make a metal peg fit tightly in a hole in a metal block, the peg is made slightly larger than the hole. The peg is then cooled down and placed in the block. Why not just heat up the block instead?

★★ **44** You have two steel meter rulers: one made of carbon-steel and one made of nickel-steel. In the laboratory at 20°C they have exactly the same length of 1.000 m. They are both heated over Bunsen burners to 800°C. Calculate how their lengths would compare if you could measure them without burning your fingers. You look up a thermal expansion table and find that a 1.0 m length of carbon-steel expands by 11 μm for each 1°C increase in temperature, whereas nickel-steel increases by just 1.3 μm.

★★★ **45** There is a device inside many older lasers consisting of a ruby rod 30.00 cm long. The working temperature of the rod can get as high as 55°C.

- **a** Calculate the increase in length for the 30 cm rod of ruby when it heats from 15°C to 55°C. You are told that a 1.00 m rod of ruby increases in length by 9.0 μm for each 1°C rise in temperature;
- **b** Determine how many wavelengths of blue laser light this increase in length is equal to given the wavelength of blue laser light is 473 nm. Note: nano, $n = 10^{-9}$.

★★★ **46** Overhead power wires out on the street are made of aluminium and strung between poles 35.0 m apart. In mid-winter a particular wire had contracted because of the cold and had no sag. In summer when the temperature was really hot, the wire increased in length by 33.3 mm. Calculate the how much the centre of the wire sagged from the horizontal. Make whatever assumptions you need.

Investigate, evaluate and communicate

★★★ **47** Propose what salt (NaCl) must do to the force of attraction between water molecules given that salty water heats up quicker than an equal mass of distilled water when the same amount of heat energy is added to both.

★★ **48** A 100.00 m long steel water pipe was laid in the ground on a hot summer's day when the temperature was 25°C. By what length would it have contracted if the ground temperature fell to –15°C?

★★ **49** Suppose a steel meter ruler made of steel and one made of invar (an alloy of iron and nickel with a coefficient of thermal expansion of 1.3×10^{-6} K⁻¹) are the same length at 0°C. What is their difference in length at 22.0°C?

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