8.1 Introduction to Thermal Energy —Kinetic Molecular Theory

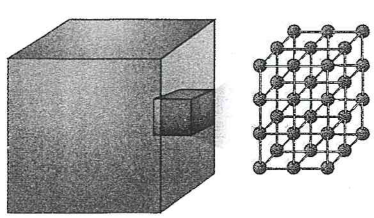
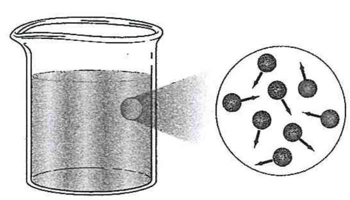
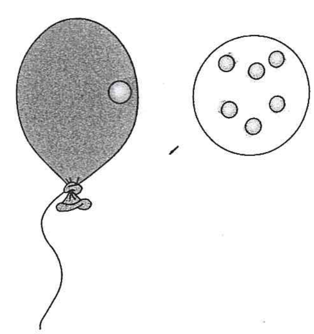
How do you feel right now? If you are ill, you may be running a fever, i.e., your body temperature may be higher than normal. You may not be able to concentrate while reading this text because the temperature of the room is too hot or too cold. You may also be reading this book waiting for your hot chocolate to cool. All of these cases show how important heat and temperature are to us.

Heat is the energy of motion or the kinetic energy of matter at the atomic and molecular levels. In 1827, Robert Brown observed the vibration of pollen grains bombarded by air particles. He concluded that all matter at the molecular level moves constantly in a random and erratic fashion. We call this motion **Brownian motion**. Since that time, other scientists, including Albert Einstein, have further developed what is now called the kinetic molecular theory and have used its ideas to solidify current ideas of atomic theory.

The main postulates of the **kinetic molecular theory** are:

- All matter is made up of small, constantly moving particles called atoms and groups of atoms called molecules.
- These atoms and molecules exert forces on one another that keep them a certain distance apart. If they move too close to each other, a repulsive force pushes them apart. Likewise, if they move too far apart, an attractive force brings them together.
- The distances between molecules and the strength of force between them is responsible for the three physical states of matter: solid, liquid, and gas. The major features of the three states of matter are outlined in Table 8.1.

Table 8.1
The States of Matter

Solids	Liquids	Gases
In solids, strong forces hold the vibrating atoms and molecules so closely that they remain in a fixed position, giving solids their rigid nature.	In liquids, vibrating atoms are still bound together, but with greater speeds, these particles may move from place to place in the liquid. Liquids clump together, but they are less rigid than solids and can take the shape of the container they are in without changing volume.	The particles that make up gases are held by even weaker forces of attraction. These faster-moving particles tend to "get as far away from each other as possible." Gases expand in volume to take the shape of the container they are in.
Fig.8.1 	**Fig.8.2** 	**Fig.8.3** 

The motion of these molecules is due to energy transformations between electrostatic potential energy and particle kinetic energy. The total thermal energy must take into account both of these energies.

In the next few sections, we will be discussing heat or thermal energy and the impact that it has on our lives.

1. Use the kinetic molecular theory to describe the differences in molecular motion in the three states of matter.
2. Describe what heat is in terms of kinetic energy.

8.2 Thermal Energy and Temperature

As all particles of matter are constantly moving and interacting in a random fashion, the actual amount of energy that they possess is too difficult to quantify because it is constantly fluctuating. **Temperature** is simply a way to measure the *average* kinetic energy of all of the particles in a quantity of matter. There are various ways of measuring the temperature of a substance. All of them show a visible change when the average kinetic energy of the substance they are measuring changes.

Thermal expansion is the increase in volume of a substance when it is heated. Thermal energy increases the atomic and molecular kinetic energies of the particles that make up the substance, causing an increase in the average distance between them.

A **thermometer**, a device for measuring temperature, operates according to the principle of thermal expansion. Table 8.2 describes different kinds of thermometers.

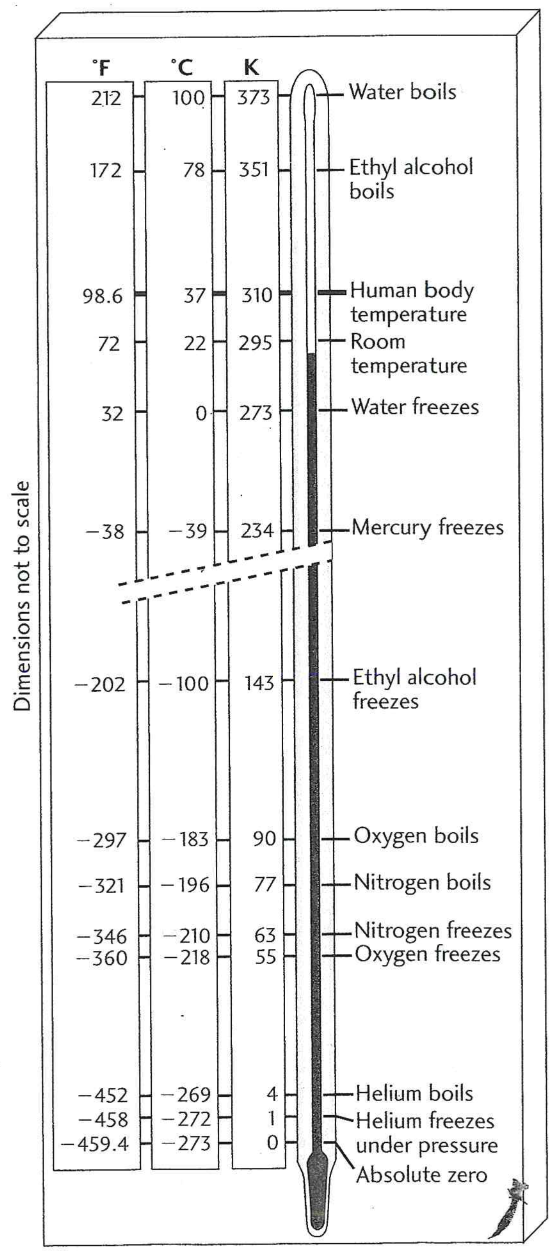
Before you can use a thermometer to measure temperature, you first need to *calibrate* it using reference points and a scale or unit of measure. Several different temperature scales have been used since thermometers were invented. Figure 8.4 shows the relationship between three common scales.

Fahrenheit. Daniel Fahrenheit used the lowest temperature of an ice-salt bath and body temperature to calibrate his thermometers. On this scale, freezing and boiling points appeared at 32 °F and 212 °F, respectively.

Celsius. Anders Celsius used the freezing and boiling points of water for his two calibration points of reference. He then divided this range into 100 degrees. *A lowercase* t *represents Celsius temperature.*

Kelvin. William Thomson (Lord Kelvin) devised a scale to put zero at the lowest possible temperature, when all molecular

Fig.8.4 A comparison of three different temperature scales

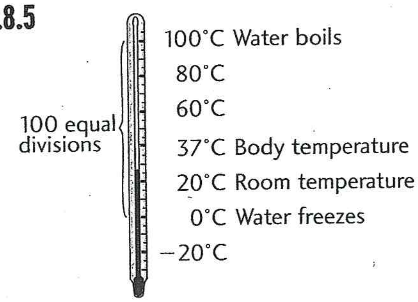
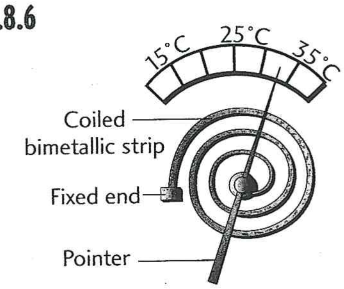


Physical chemists use Charles' law $\left(\frac{V_1}{T_1} = \frac{V_2}{T_2}\right)$ to describe the relationship between the volume (V) and the temperature (T) of gases at constant pressure. If we use the Celsius scale for temperature, at 0°C, the ratio $\frac{V}{T}$ is undefined, so instead they use the Kelvin scale.

motion stops. The size of a degree Kelvin is the same as that of a degree Celsius. The lowest temperature is called absolute zero and is determined experimentally to be −273°C. The SI unit of temperature is the kelvin (K) without a ° symbol. The freezing point of water is 273 K and the boiling point of water is 373 K.

The Celsius scale was used in the original metric system. The Kelvin scale is required in many branches of science with calculations involving temperature. *An uppercase* T *represents Kelvin temperature.*

Table 8.2
Types of Thermometers

<table>
<tr><th>Thermometer</th><th>Construction</th></tr>
<tr><td>Liquid Filled Thermometer A trapped liquid expands when heated and contracts when cooled. In a long thin tube, a liquid column moves up and down in relation to the temperature.</td><td>Fig.8.5

</td></tr>
<tr><td>Bimetallic Thermometer Two dissimilar thin metal ribbons are bonded together. When the temperature changes, they expand or contract at different rates, which causes the ribbon to bend in one direction or another. In a coiled format, this bending causes an indicator to rotate against a graduated scale.</td><td>Fig.8.6

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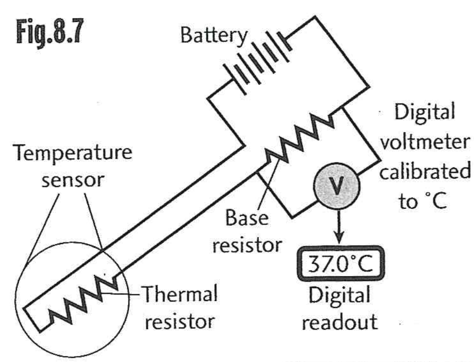
<tr><td>Thermal Resistor An electrical resistor (see Chapter 16) has a resistance that depends on temperature. A higher temperature increases the electrical resistance, which shows up as a change on an electric meter. The thermometer converts the voltage change into a temperature, which is displayed digitally.</td><td>Fig.8.7

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1. Adding heat increases molecular motion and causes materials to expand. How are temperature and heat related?
2. What are the three different temperature scales and where are they used?

8.3 Heat—Thermal Energy Transfer

Place your hand on a piece of wood, perhaps your desktop. Take note of the warmth of the material. With the same hand, grasp something that is metal, such as the leg of your chair or a metal table leg. You are sure to have noticed a difference in the perceived temperature between the wooden and the metal object. In actual fact, if they have been in the same room for a while, they are at the same temperature. Our body doesn't measure temperature. Instead, it registers thermal energy flow or the movement of thermal energy into or out of the body. When we feel cold, we are actually registering heat flowing out of our body. In fact, there is no such thing as cold or hot, only a deficit or excess of heat.

In Chapter 7, we studied the law of conservation of energy. We found that when energy is transferred from one form to another in a closed mechanical system, none of it is lost. But we did not measure any conversions to heat energy.

Heat is the flow of thermal energy from an object of high temperature to an object of low temperature.

In 1847, James Joule showed that energy is conserved when it is converted from gravitational potential energy to heat energy. He used an apparatus like the one shown in Fig. 8.8. As the falling masses lose gravitational potential energy, the vanes (or paddles) stir the water, which results in a notable rise in temperature of the water. This temperature rise signifies an increase in the water's thermal energy. Joule was able to show quantitatively that the decrease in gravitational potential energy caused the increase in the thermal energy of the system.

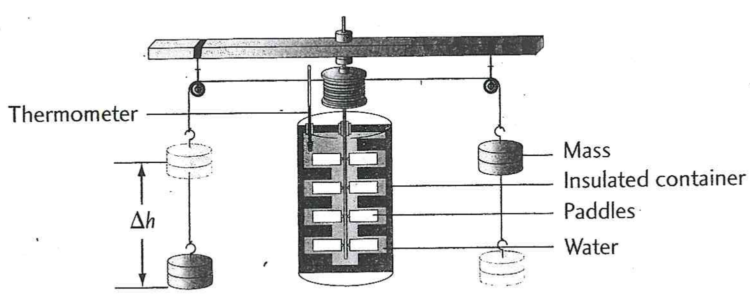


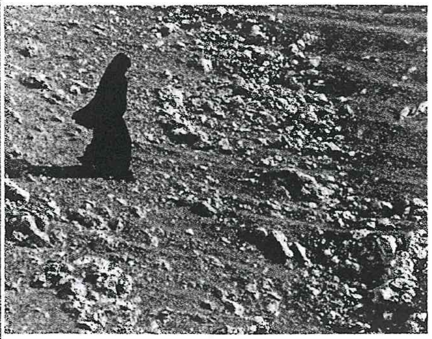
Fig.8.8 Conversion of mechanical energy to heat

Methods of Heat Energy Transfer

Heat is transferred from one point to another by three possible methods: conduction, convection, and radiation.

Conduction is the process of transferring heat by particle collision. Figure 8.9 shows how heat conducts along the length of a piece of metal

Fig.8.17



The robes worn by Bedouins in the Sinai desert are black. This fact seems to contradict the concepts you have learned. However, upon closer examination of the situation, we see that even though the black robe is 4–6° higher in temperature than the white robe, the black robe causes more convection under it by warming the air to a higher temperature than the white robe. The warmer air rises faster and leaves through the pores and openings of the material. This causes external air to be drawn in from the large, open end at the bottom of the robe. The increased circulation keeps the person cool.

Set-back timer/thermostat for home heating and air conditioning minimizes the temperature difference between inside and outside the home, reducing heat flow inside or out, which can save you money.

Table 8.4
Specific Heat Capacities

Material	Specific heat capacity (J/kg°C)
Liquid nitrogen	1.1×10^2
Gold	1.3×10^2
Lead	1.3×10^2
Mercury	1.4×10^2
Steam	2.0×10^2
Silver	2.3×10^2
Ethyl alcohol	2.4×10^2
Glycerine	2.4×10^2
Methyl alcohol	2.5×10^2
Brass	3.8×10^2
Copper	3.9×10^2
Iron	4.6×10^2
Crown glass	6.7×10^2
Pyrex®	7.8×10^2
Granite	8.0×10^2
Sand	8.0×10^2
Aluminium	9.1×10^2
Air	1.0×10^3
Wood	1.8×10^3
Ice	2.1×10^3
Concrete	2.9×10^3
Water	4.2×10^3

8.4 Specific Heat Capacity

Heat transfer to any substance depends on three things:

Temperature difference. The greater the temperature difference between the hot and cold substance, the greater the heat flow.

Mass of substance. The more mass a substance has, the more molecules need to have thermal energy transferred to or from them.

Type of substance. Different substances are held together by their own specific intermolecular forces and accept the transfer of heat to different extents.

Two separate pots are heated on a stove under the same conditions, one pot containing water and the other containing vegetable oil. The temperature of the oil rises at a faster rate than the water temperature, but the water starts to boil at a lower temperature. This phenomenom is a property of matter that describes the thermal differences between materials, called the **specific heat capacity**.

Specific heat capacity is the amount of heat energy that is needed to increase the temperature of 1 kg of a particular substance by 1°C.

The units of heat capacity are J/kg°C and its symbol is given as c. The specific heat capacities (c) for water and several other common substances are given in Table 8.4.

The greater the value of the specific heat capacity, c, the more heat energy must be transferred to the substance to change its temperature by one degree Celsius.

The mathematical formula for calculating heat transfer is

$$\Delta E_{\mathrm{H}} = mc\Delta t$$

where ΔE_{H} is the heat energy transferred to or from a substance in joules (J), m is the mass of the substance in kilograms (kg), Δt is the temperature change of the substance in °C, and c is the specific heat capacity of the substance in J/kg°C.

EXAMPLE 1 Heating copper

How much heat energy is required to heat a 1.0 kg piece of copper pipe from 25.0°C to 66.0°C?

Solution and Connection to Theory

Given

$m = 1.0$ kg $t_1 = 25.0°C$ $t_2 = 66.0°C$ material is copper $\Delta E_H = ?$

We can find the specific heat capacity (c) of copper in Table 8.4.

$c_{copper} = 3.9 \times 10^2$ J/kg°C

Substituting into the equation,

$$\Delta E_H = mc\Delta t = mc(t_2 - t_1) = 1.0\text{ kg}(3.9 \times 10^2\text{ J/kg°C})(66.0°C - 25.0°C)$$
$$= 1.0\text{ kg}(3.9 \times 10^2\text{ J/kg°C})(41.0°C)$$

$$\Delta E_H = 1.6 \times 10^4\text{ J}$$

Therefore, the heat energy E_H required to heat a 1.0 kg piece of copper pipe from 25.0°C to 66.0°C is 1.6×10^4 J.

If the copper was cooled instead of heated, the value for E_H would be negative because the two temperature values would be reversed, making Δt negative. This means that for a substance, a positive ΔE_H means it is warming and a negative ΔE_H means that it is cooling.

EXAMPLE 2 Cooling iron

A 0.50 kg block of iron at 80.0°C is cooled by removing 2.28×10^4 J of heat energy. What will the final temperature of the metal be?

Solution and Connection to Theory

Given

$m = 0.50$ kg $t_1 = 80.0°C$ $\Delta E_H = -2.28 \times 10^4$ J material is iron $t_2 = ?$

The word "removing" indicates that E_H is negative. From Table 8.4, the specific heat capacity for iron is 4.6×10^2 J/kg°C.

$$\Delta E_H = mc\Delta t = mc(t_2 - t_1)$$

$$t_2 = \frac{E_H}{mc} + t_1$$

$$t_2 = \frac{-2.28 \times 10^4\text{ J}}{(0.50\text{ kg})(4.6 \times 10^2\ \frac{\text{J}}{\text{kg}\cdot°\text{C}})} + 80.0°C$$

$$t_2 = -99.13°C + 80.0°C = -19°C$$

Therefore, the final temperature for this piece of iron is −19°C.

APPLYING the Concepts

1. What three things does heat transfer depend on?
2. Answer Question 2 at the end of Section 8.3 (holding onto a metal pole in the cold as opposed to a wooden one) by using the values for specific heat capacity in Table 8.4.
3. Compare the heat required to heat 1.5 kg pieces of gold (we wish), iron, and silver from 12°C to 40°C. How does the solution change when these materials are cooled?

8.5 Heat Exchange — The Law of Conservation of Heat Energy

In the previous section, we examined what happens to the temperature of a specific substance when heat is either added or taken away. According to the law of conservation of energy, the total amount of heat energy must be constant as long as none of it is lost to the surroundings. If we think of heat energy as moving from a hot object to a cold object, then we can simplify the law of conservation of heat energy to be

$$|E_{H_{lost}}| = |E_{H_{gained}}| \text{ or}$$

$$\Delta E_{H_1} = -\Delta E_{H_2}$$

Because this application of the law of conservation of energy specifically involves the exchange of heat energy, this principle is also called the **principle of heat exchange**. The negative sign represents the direction in which heat is flowing. It shows that the values of E_H are the same, but one material is losing heat while the other one is gaining heat.

EXAMPLE 3 **A spot of tea?**

A 0.500 kg pot of hot water for tea has cooled to 40.0°C. How much freshly boiled water must be added (at 100.0°C, of course) to raise the temperature of the tea water to a respectable 65.0°C?

Solution and Connection to Theory

Given

cool water

$m_c = 0.500$ kg

$c_w = 4.2 \times 10^3$ J/kg°C

$t_1 = 40.0°C$, $t_2 = 65.0°C$

$\Delta t_c = (65.0°C - 40.0°C) = 25.0°C$

hot water

$m_h = ?$

$c_w = 4.2 \times 10^3$ J/kg°C

$t_1 = 100.0°C$, $t_2 = 65.0°C$

$\Delta t_h = (65.0°C - 100.0°C) = -35.0°C$