CHAPTER 7

Model of Matter – The Particulate Nature of Matter

Introduction

In this chapter, we will learn how the particulate nature of matter is used as a model to explain the physical properties of different states of matter. We will also learn how this model is used to explain the behaviour of particles upon cooling or heating. This model will help us appreciate natural phenomena such as diffusion and osmosis.

Learning Map

This table shows the content covered in this chapter relating to the Primary Science (PS), Lower Secondary Science (LSS) and Upper Secondary Science (USS) syllabuses.

Content	PS	LSS	USS
Matter has mass and volume	✓	✓	✓
Differentiating between the three states of matter (solid, liquid, gas) in terms of their shapes and volumes	✓	✓	✓
Relating the change in temperature of an object to the gain or loss of heat by the object	✓	✓	✓
Water and its three interchangeable states	✓	✓	
The effect of heat gain and heat loss on the temperature and state of matter	✓	✓	✓
Processes involving heat gain and heat loss: melting, boiling, condensation and evaporation	✓	✓	✓
Effects of heat gain and heat loss in our everyday lives involving contraction and expansion	✓	✓	✓
Brownian motion experiments as the evidence for the movement of particles		✓	✓
Particulate nature of matter being a model representing matter		✓	✓
Describing the arrangement and movement of the particles in matter in the solid, liquid and gaseous states, using the particulate nature of matter		✓	✓
Diffusion		✓	✓

Prior Knowledge

In Primary Science, you had learnt the following:

Topics: Matter, heat and temperature, water and three interchangeable states of matter

- Matter has mass and volume.
- The three states of matter are solids, liquids and gases.
- Matter expands when it gains heat, and contracts when it loses heat.
- During heat gain and heat loss, matter undergoes a change in its state.
- Changes in state that involve heat gain are melting and boiling.
- Changes in state that involve heat loss are freezing and condensation.

7.1 The Particulate Nature of Matter

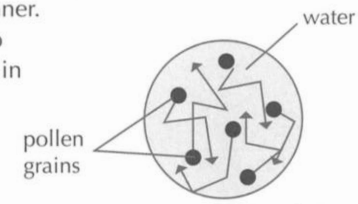
Learning Outcomes

You should be able to:

- appreciate scientific attitudes in creating models to explain the fundamental nature of things and re-examine existing models, e.g., creativity, open-mindedness and attitudes required to derive the particulate nature of matter
- understand that the particulate nature of matter is a model representing matter that is made up of small discrete particles in constant and random motion

Brownian Motion — Evidence Showing That Particles Are Moving

- In 1827, Robert Brown, a botanist, observed under a microscope, some pollen grains floating on water.
- He noticed that the pollen grains were moving around in a random manner.
- Water particles cannot be seen. However, water particles can bump into the pollen grains from different sides, causing the pollen grains to move in a random manner as shown in the figure.
- This random movement of small particles in liquid or gas is known as Brownian motion.
- Hence, Brownian motion proves that matter is made up of small and discrete particles that are in constant and random motion.



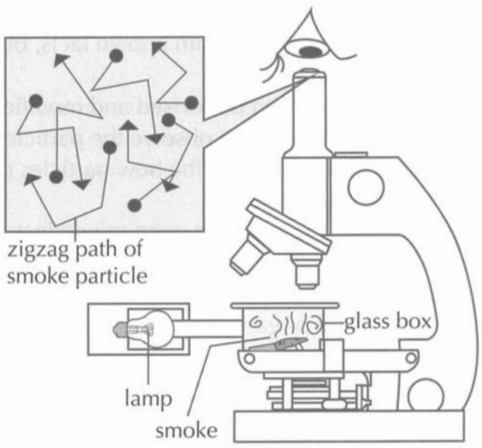
Movement of pollen grains observed under a microscope

Tip

When drawing the zigzag path of each particle, the changes in the moving direction of the particle must be random.

Brownian Motion and Smoke Particles

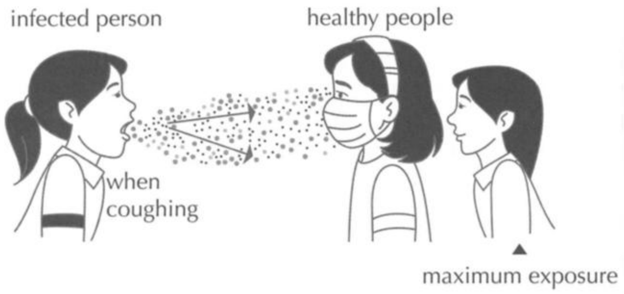
- In an experiment carried out to observe Brownian motion of smoke particles, a light microscope is used to view smoke particles in a transparent glass box, as shown in the figure on the right.
- Under the light microscope, the smoke particles are observed to be moving randomly in zigzag paths.
- This random movement is due to collisions between the small but fast-moving air particles (which are too small to be seen) and the smoke particles (which are larger and can be seen).
- The smoke particles in the glass box are constantly bombarded from all sides by the air particles.
- This is the evidence of air particles moving randomly.

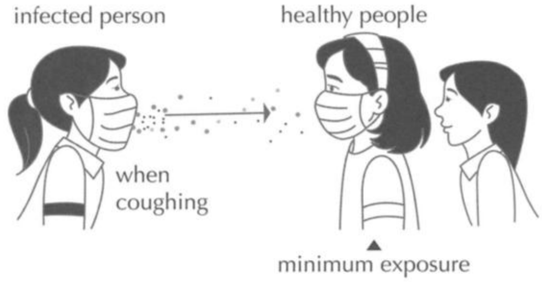


Brownian Motion and Infectious Diseases

- Brownian motion can be used to explain the transmission of diseases through air.
- Diseases that can be spread through air are known as airborne diseases. Examples are the common cold, influenza, SARS and COVID-19.
- The SARS and COVID-19 pandemics are examples of disease outbreaks that had spread across countries, infecting and killing many people.
- Airborne diseases can be spread when infected people cough, sneeze or talk, spewing nasal and throat secretions into air. Some droplets carrying the virus may land on other people or surfaces.
- When the water evaporates from the droplets in the air, the viral particles are left behind.

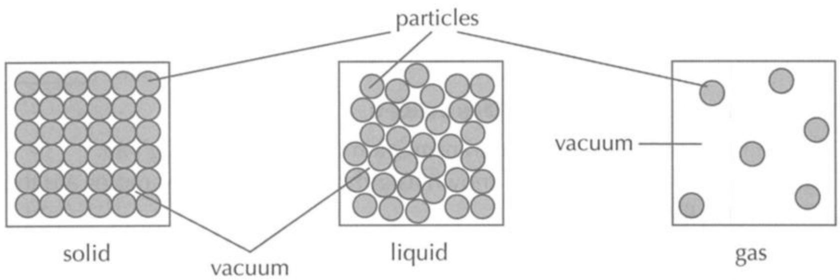
- Due to Brownian motion, these particles move randomly. This can result in the transmission and spreading of the viruses to people in the vicinity.
- Therefore, wearing a mask can help to reduce the spread of airborne diseases, as illustrated in the figure below.





Particulate Nature of Matter

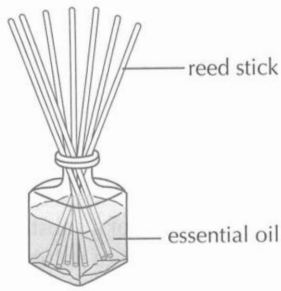
- In science, many ideas can be abstract or difficult to observe. Thus, scientists construct models to help them visualise and understand these abstract ideas.
- Models can consist of words, diagrams, formulae, mathematical equations and physical models.
- Models are used to explain known facts, observations and phenomena. They can also be used to make predictions.
- Existing models can be revised and modified to provide better description and explanation.
- Since we are unable to observe the particles of matter, models are constructed based on the particulate theory of matter to describe how particles move and are arranged at different states of matter, which are the solid, liquid and gas.
- Scientific attitudes such as open-mindedness, willingness to challenge assumptions and re-examining existing models had led to the discovery of Brownian motion, hence deriving the particulate nature of matter.
- In this model, each particle is represented with a circle, as shown in the figure below. The particle can be a solid, liquid or gas. The spaces between the particles are vacuum and not occupied by any matter.



Tip
Particles can be atoms, molecules or ions.

Worked Example 1

The figure on the right shows a reed diffuser commonly used at home. It is a liquid air freshener where long reed sticks are inserted into the liquid essential oil.



Joseph has bought a reed diffuser and placed it at a corner of his living room.

Based on the particulate nature of matter, explain why Joseph is able to smell the essential oil in his entire living room after an hour.

Answer

The reed sticks absorb the essential oil, which then evaporates. The particles of the essential oil are bombarded by the surrounding air particles that are moving quickly in random directions. Thus, the essential oil particles spread to other parts of the living room.

Tips

- Essential oils are usually volatile and evaporate easily at room temperature.
- The air particles in the surroundings push these essential oil particles around from a region of higher concentration to a region of lower concentration till the entire room is filled with the essential oil particles. This process is called diffusion, which will be covered in Section 7.4.

7.2 Using the Particulate Nature of Matter to Explain the States of Matter

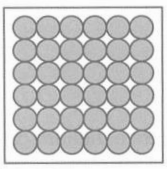
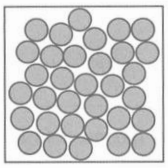
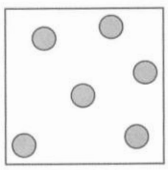
Learning Outcome

You should be able to:

- use the particulate nature of matter to describe the arrangement and movement of the particles in matter in the solid, liquid and gaseous states

Three States of Matter

- Matter is anything that has mass and occupies space.
- Matter can be classified based on its physical states: solid, liquid and gas.
- The table below describes the arrangement, movement and forces of attraction of particles in matter using the particulate of matter.

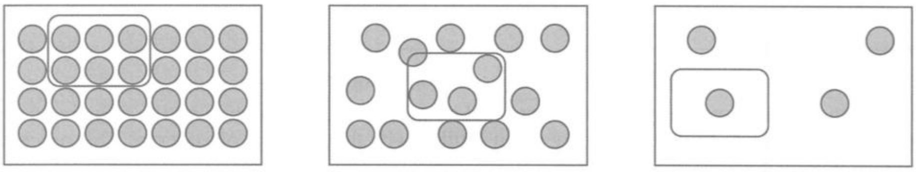
State	Solid	Liquid	Gas
Movement of Particles	Vibrate in a fixed position	Slide past one another	Move at high speeds randomly in all directions
Arrangement of Particles	Very closely packed in an orderly arrangement	Closely packed in an disorderly arrangement	Far apart from one another in a disorderly arrangement
Force of Attraction Between Particles	Strong	Moderately strong	Very weak
Diagrammatic Representation			

Tips

- In Primary Science, ice, water and water vapour/steam are the common examples used to show the three states of matter.
- In Secondary Science, it is useful to know the physical state of common examples at room temperature. For example, at room temperature, mercury and alcohol are liquids, whereas chlorine, ammonia and hydrogen are gases.

Volume and Density

- The density of a substance is the amount of matter per unit volume of the substance.
- For each unit of volume, there are more particles packed in a solid than in a liquid, which contains more particles than a gas, as shown in the figure below. Therefore, the density of a substance in the solid state is usually the highest, followed by the liquid state and then the gaseous state.



- The table below compares the volumes and densities of solids, liquids and gases.

State	Solid	Liquid	Gas
Volume	Definite	Definite	Indefinite
Explanation	Particles are packed very closely together.	Particles are packed closely together.	Particles are far apart.
Density for the Same Mass of Substance	Since the volume is smallest, the density is highest.	Since the volume is small, the density is high.	Since the volume is largest, the density is lowest.

Tip

Even in the liquid state, the particles are still closely packed even when they can move around and slide past one another. Hence, the density of a substance in the solid and liquid states is higher than that in the gaseous state.

Worked Example 2

Study the list of substances below.

- oil
- common salt
- helium
- water

Which one of the substances can be compressed at room temperature?

Answer

Helium

Tip

Helium is a gas at room temperature. A gas has no definite volume. Hence, helium can be compressed.

Worked Example 3

The densities of copper in the solid and liquid states are approximately 8.96 g/cm^3 and 8.02 g/cm^3 respectively.

Explain why the density of copper in the solid state is higher than that in the liquid state.

Answer

The copper atoms are more closely packed in the solid state than in the liquid state. Hence, in the solid state, the volume of copper is smaller and its density is higher.

Tip

The density of a substance is the amount of matter per unit volume of the substance. Hence, the density of matter in the solid state is usually the highest, followed by the liquid state and then the gaseous state.

7.3 Behaviour of Particles Upon Heating and Cooling

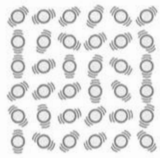
Learning Outcomes

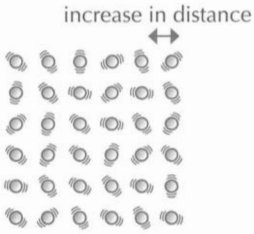
You should be able to:

- use models to explain expansion and contraction, and the conservation of mass during these processes
- *use models to explain melting and boiling in terms of conversion of the three states of matter

Matter Expands When Heated

- When matter is heated, its particles gain energy and move faster.
- The movement of particles overcomes the forces of attraction between them, enabling them to move further apart. This is shown in the figure on the right.
- As the particles move further apart from one another, the distance between them increases, so the volume of the matter also increases.
- The size of the particles remains unchanged.
- The number of the particles remains unchanged.
- Since the volume of the matter increases, it is said to expand when heated.


low temperature



high temperature

Matter Contracts When Cooled

- When matter is cooled, its particles lose energy and move slower.
- Therefore, the particles are unable to overcome the forces of attraction between them, causing them to move closer to one another.
- As the particles move closer to one another, the distance between them decreases, so the volume of the matter decreases.
- The size of the particles remains unchanged.
- The number of the particles remains unchanged.
- Since the volume of the matter decreases, it is said to contract when cooled.

** denotes "Optional for N(A)"*

Worked Example 4

The figure on the right shows part of a road in an area that is constantly exposed to the sun.

Briefly explain how these cracks are formed on the road.

Answer

The road has gained heat from the surroundings and expanded.
When the road has expanded too much, the cracks form.

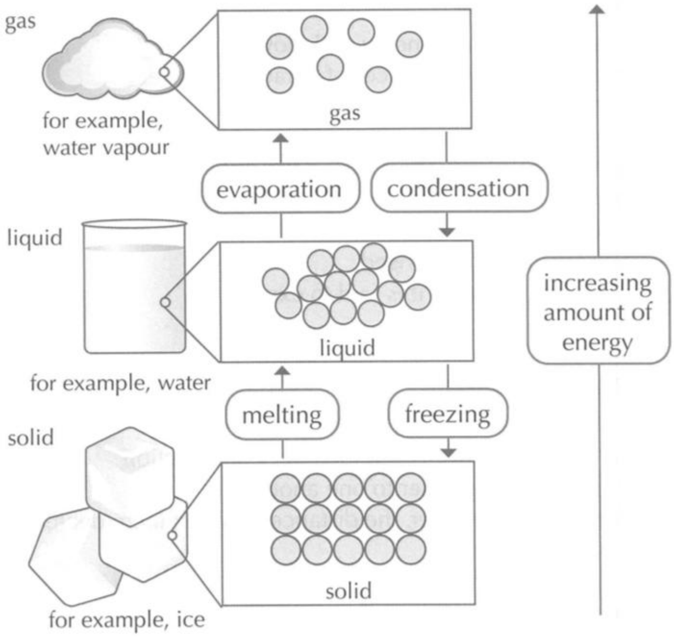
Tip

This is a real-world phenomenon. The surrounding air gains heat from the Sun on hot days. Heat is transferred to the material of the road. The particles in the material gain heat, increasing the volume of the material and causing it to expand. When there is no allowance for the road to expand, cracks form.

Optional for N(A)

Change in the State of Matter

- Matter can exist in the solid, liquid or gaseous states, depending on its temperature and atmospheric pressure. At a fixed pressure, the temperature of an object determines its state. You will learn more about pressure in Revision Guide 2A.
- The particles in solids, liquids and gases have different amounts of energy. They are also arranged differently and move in different ways.
- The figure below shows the change in the states of matter using the particulate model of matter.

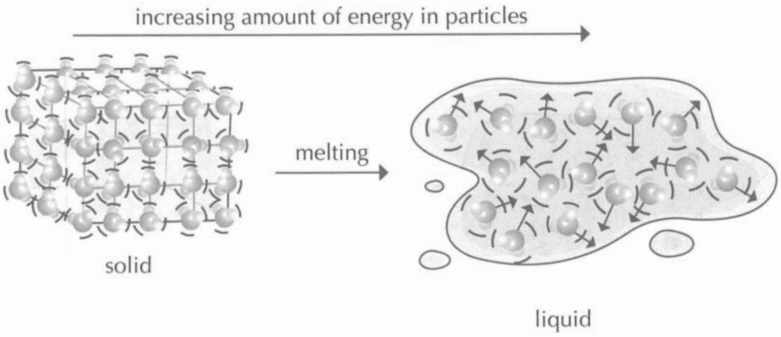


Change in the State of Matter Due to Heat Gain: Melting

- Melting is the process in which a solid changes into a liquid without a change in temperature.
- The temperature at which melting occurs is known as the melting point.
- When a solid is strongly heated, the particles gain energy and vibrate more vigorously in their fixed positions.
- When the particles have enough energy, they overcome the very strong forces of attraction between them and slide over one another.

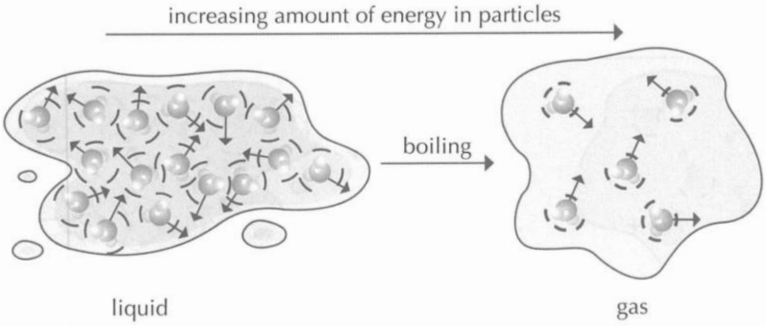
Optional for N(A)

- The particles are no longer held in fixed positions, but they are still close to one another.



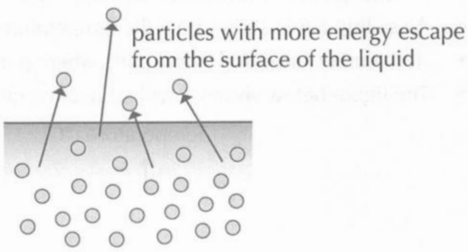
Change in the State of Matter Due to Heat Gain: Boiling

- Boiling is the process in which a liquid changes into a gas without a change in temperature.
- The temperature at which boiling occurs is known as the boiling point.
- When a liquid is heated, the particles gain energy and move faster.
- When the particles have enough energy, they overcome the forces of attraction between them.
- The particles become randomly arranged and are very far apart. They also move faster.



Enrichment

- Evaporation occurs when particles in a liquid gain sufficient energy to escape from the surface of the liquid.



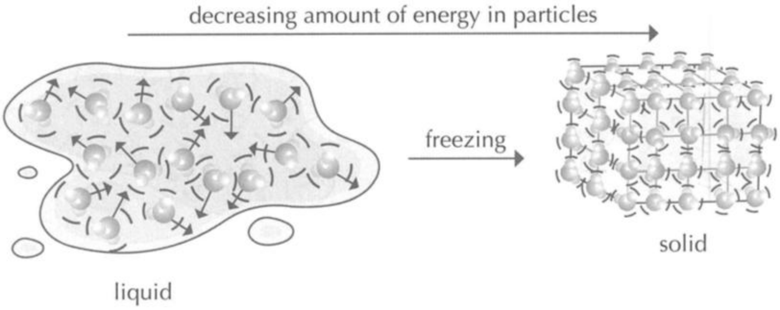
- As temperature increases, more particles have enough energy to escape from the liquid surface. Hence, the rate of evaporation of a liquid is higher at higher temperatures.

Change in the State of Matter Due to Heat Loss: Freezing

- Freezing is the process in which a liquid changes into a solid without a change in temperature.
- The temperature at which freezing occurs is known as the freezing point.
- When a liquid is cooled, the particles lose energy and move more slowly.

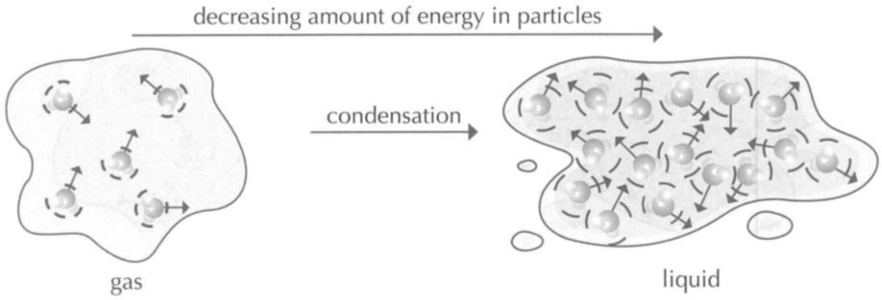
Optional for N(A)

- As temperature decreases, the particles lose more and more energy until they are close enough to allow the forces of attraction to pull them back to their fixed positions.
- The substance has changed from a liquid to a solid.



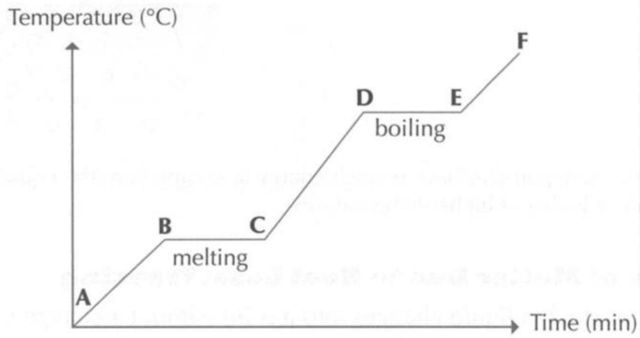
Change in the State of Matter Due to Heat Loss: Condensation

- Condensation is the process in which a gas changes into a liquid without a change in temperature.
- When a gas is cooled, the particles lose energy and move more slowly.
- As temperature decreases, the particles lose more and more energy until they are pulled closer together by the forces of attraction.
- The particles are now unable to move randomly. Instead, they slide over one another.
- The substance has changed from a gas to a liquid.



Enrichment

- A heating curve shows how the temperature of a substance changes with time as it is heated up.
- A cooling curve shows how the temperature of a substance changes with time as it is cooled down.
- Both curves have horizontal parts where particles gain energy for the change in state.
- The figure below shows a typical heating curve.

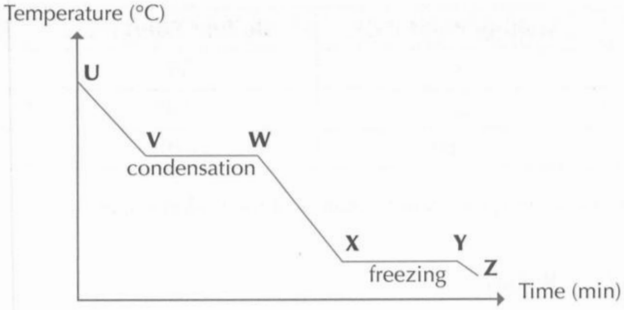


  - **A–B**: As a solid is heated, the particles in it gain energy and vibrate faster about their fixed positions. The temperature of the solid increases until it reaches point **B**, the melting point. At point **B**, the solid begins to melt.

Optional for N(A)

- **B–C**: Melting occurs at a fixed temperature for pure substances. A mixture of solid and liquid exists at this stage. Energy from heating is used to overcome the forces of attraction between the particles.
- **C–D**: At point **C**, all the solid has melted. The temperature of the liquid increases as heating continues. The particles become further apart. The temperature of the liquid increases until it reaches point **D**, the boiling point.
- **D–E**: The liquid boils. A mixture of liquid and gas exists at this stage. At this temperature, the particles have gained enough energy to overcome the forces of attraction holding them together.
- **E–F**: The substance is now a gas. The particles are spread far apart. They move randomly and quickly in any direction.

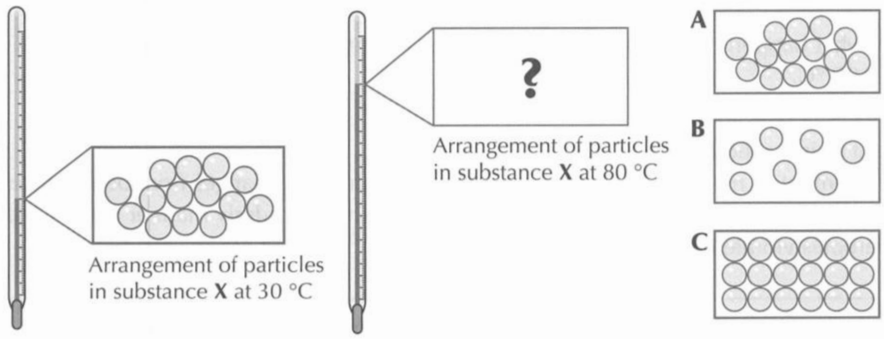
- The figure below shows a typical cooling curve.



- **U–V**: The particles in a gas lose energy and move more slowly as temperature drops.
- **V–W**: As the temperature decreases, the particles lose more and more energy until they are pulled closer together by the forces of attraction. The substance has condensed from a gas to a liquid.
- **W–X**: The particles in the liquid lose energy and move more slowly. The temperature of the liquid decreases until it reaches point **X**, the freezing point.
- **X–Y**: At point **X**, the liquid starts to freeze. A mixture of liquid and solid exists at this stage. The temperature remains constant even though cooling continues. The particles no longer have enough energy to move freely and start to settle into fixed positions.
- **Y–Z**: The particles in the solid lose energy and vibrate about their fixed positions. At point **Y**, all the liquid has frozen. The temperature of the solid continues to drop as cooling continues.

Worked Example 5

Substance **X** is an element with a boiling point of 100 °C. The figure below shows the arrangement of the particles in substance **X** at 30 °C.



Which option, **A**, **B** or **C**, shows the correct arrangement of the correct particles in substance **X** at 80 °C?

Answer

A

Optional for N(A)

Tips

- The figure shows that the particles are closely packed but able to slide over one another at 30 °C. Based on the particulate model of matter, substance **X** is in the liquid state at 30 °C.
- Since the boiling point of substance **X** is 100 °C, substance **X** is still in the liquid state at 80 °C. There is no change in the state of substance **X** from 30 °C through 80 °C.

Worked Example 6

The table below shows the melting points and boiling points of three elements **P**, **Q** and **R**.

Element	Melting Point (°C)	Boiling Point (°C)	State of Matter at 30 °C
P	−31	357	
Q	50	385	
R	−210	−196	

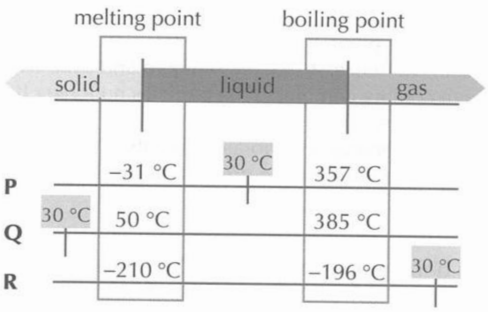
(a) Complete the table by indicating the state of matter of each element at 30 °C.

Answer

P: Liquid **Q**: Solid **R**: Gas

Tip

We can determine the state of matter of each substance at a particular temperature by sketching lines as shown in the figure below. (***Note:*** *The figure is not drawn to scale.*)



(b) Describe what happens to the arrangement and movement of particles when element **Q** is heated from 30 °C to 100 °C.

Answer

- Element **Q** is a solid at 30 °C.
- When element **Q** melts at 50 °C, the arrangement of particles changes from being closely packed and arranged in an orderly manner to being arranged in a disorderly manner but still closely packed.
- The particles vibrate faster and slide past one another.

Tips

- For this type of question, take note of the melting and boiling points of the substance.
- If heating starts before the melting point and stops after the melting point, the substance changes from the solid state to the liquid state.
- If heating starts before the boiling point and stops after the boiling point, the substance changes from the liquid state to the gaseous state.

7.4 Diffusion of Particles

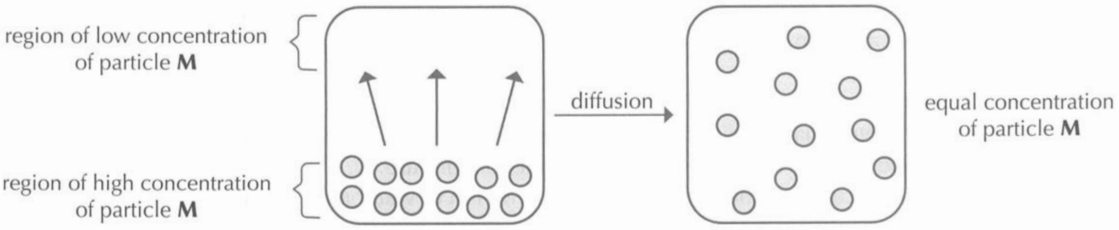
Learning Outcome

You should be able to:

- understand that diffusion is the net movement of particles from a region of higher concentration to a region of lower concentration

Diffusion

- Particles are in constant and random movement.
- Diffusion is the net movement of particles from a region of higher concentration to a region of lower concentration until both regions are of equal concentration.



- Concentration is the number of particles per unit volume. A higher concentration means that there are a greater number of particles per unit volume.
- Diffusion stops when the particles are evenly spread out.

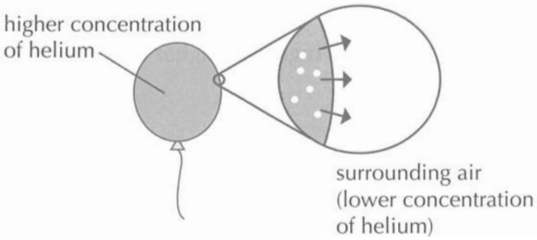
Tips

- Diffusion is the idea of particles spreading out to fill up the space that is available to them.
- Diffusion takes place in fluids (i.e., liquids and gases) but not solids. Diffusion in liquids is much slower than in gases.
- Diffusion also occurs in living systems. For example, oxygen is taken into the body cells for respiration by diffusion. Water is absorbed into the root cells by diffusion.

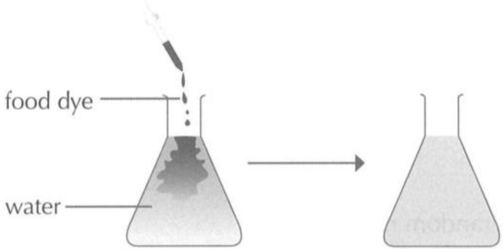
- Diffusion is a passive movement that occurs naturally, so no external energy is required.
- The diffusion of one substance is not affected by the concentration of another substance.

Examples of Diffusion in Our Daily Lives

- Common examples of diffusion that occur in our daily lives:
  1. Helium balloon
     - A helium balloon deflates slowly and becomes no longer able to float in the air.
     - This happens because helium diffuses from the helium-rich area (inside the balloon) to the helium-poor area (surrounding air) through the material of the balloon.

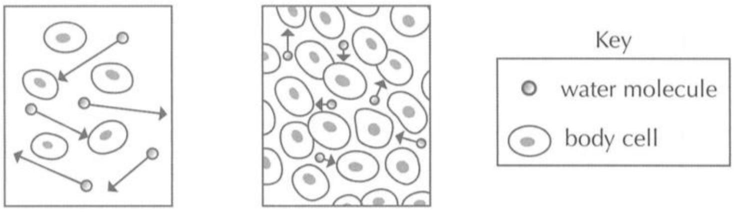


2. Food colouring
   - When a drop of food dye is added to water in a container, the dye particles move from a region of higher concentration to a region of lower concentration until the entire container of water is coloured.



3. Perfume
   - When perfume is sprayed at one part of a room, it spreads throughout the whole room due to diffusion from a region of higher concentration to a region of lower concentration.

4. Medical imaging
   - Diffusion-weighted magnetic resonance imaging (MRI) is introduced into clinical practice to detect and assess body tissues that undergo changes due to a disease.
   - Diseased tissues can alter the random Brownian motion of water molecules in them.
   - In image **A** below, water molecules (represented by small circles) diffuse freely within the spaces between cells in a normal tissue.



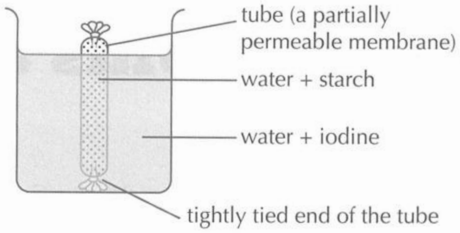
A: normal tissue **B:** diseased tissue

   - In image **B**, restricted diffusion happens in diseased tissue. For example, in a tumour where groups of abnormal cells grow rapidly and form a lump, water molecules collide frequently with these cells. Hence, the free movement of water molecules is impeded.
   - The diffusion-weighted images produced are therefore based on the differences in the rate of diffusion of water molecules in the normal and diseased body tissues.
   - This medical imaging technology enables doctors to differentiate the normal and diseased tissues, and provides some information on the stage of the disease in the patient.

5. Carbonated drink
   - A cup of carbonated drink goes flat after a while.
   - This is because the carbon dioxide concentration is higher in the drink in the cup than the surrounding air.
   - Hence, carbon dioxide diffuses from the region of higher concentration (drink) to the region of lower concentration (surrounding air).

Worked Example 7

The figure on the right shows a tube containing starch. The tube is placed inside a beaker of iodine solution. Iodine solution turns from brown to blue-black when it comes into contact with starch. The tube is a partially permeable membrane that allows the iodine molecules to pass through but not the starch molecules.



(a) After 30 minutes, the content inside the tube turned blue-black. State the process that has taken place.

Answer

Diffusion

(b) Explain the observation in **(a)**.

Answer

The iodine molecules have moved from a region of higher concentration in the iodine solution to a region of lower concentration in the tube by diffusion. Iodine turned blue-black in the tube as it came into contact with starch.

Tip

The partially permeable membrane allows the smaller iodine molecules to pass through but not the larger starch molecules. Hence, only the content in the tube turns blue-black as the iodine molecules diffuse into the tube, while the starch molecules remain inside the tube.

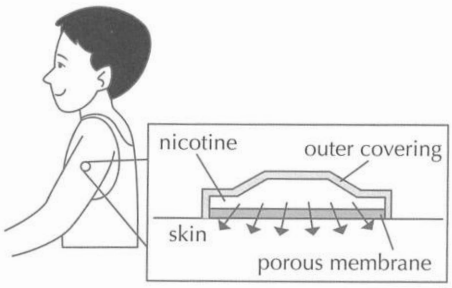
Worked Example 8

A nicotine patch is a form of adhesive patch that aims to help smokers quit smoking. The patch contains a small amount of nicotine. After the inner protective layer is peeled off, the patch is pasted on the skin to release nicotine in controlled doses into the blood vessels under the skin.

Suggest how the nicotine in the patch reaches the bloodstream.

Tip

Recall the principle of diffusion.



Answer

- The concentration of nicotine in the patch is higher than that in the blood vessels under the skin.
- After the patch is pasted on the skin, nicotine diffuses from a region of higher concentration in the patch to a region of lower concentration in the bloodstream under the skin.