7 Kinetic Particle Model of Matter

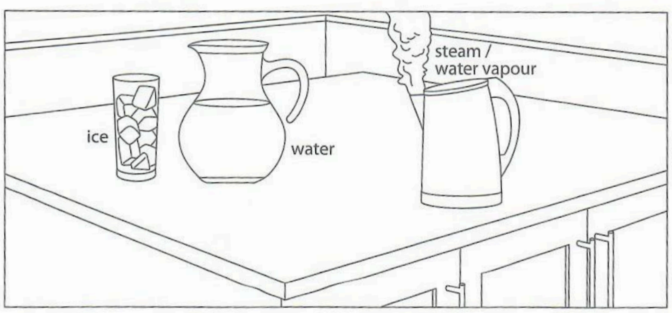
Study Station ▸▸

A States of Matter in Kinetic Particle Model

Learning Outcomes

- Compare the physical properties of the different states of matter (solids, liquids and gases).
- Use the kinetic particle model of matter to describe solids, liquids and gases, relating their physical properties to the arrangement and motion of the particles (molecules, atoms) and the forces and distances between particles.

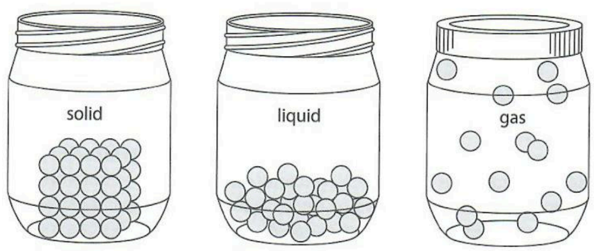
1. The **kinetic particle model of matter** is used to *understand the three states of matter* (i.e. solid, liquid and gas) and *the differences in their physical properties* (e.g. shape and volume).
2. In a kitchen, we can easily find water in the state of solid (ice), liquid (water) and gas (steam/water vapour).



	Ice	Water	Steam / Water Vapour
Shape	Has a fixed shape	Changes shape as it flows	Does not have a fixed shape
Volume	Has a fixed volume (due to the fixed shape)	Has a fixed volume (takes the same amount of space when it changes shape)	Does not have a fixed volume (it can expand or be compressed)

3. **The kinetic particle model** is a way to explain these differences by *representing* the water *molecules* as tiny, hard spheres called *particles* that are constantly moving.

4. In the kinetic particle model, the *arrangement, motion and interactions between the particles* are different in each state of matter.



The 3D diagram of the kinetic particle model for each state of matter

Solid	Liquid	Gas	
Particles are closely packed together	Particles are loosely packed together	Particles are very far apart	**Amount of space** increases
Particles are arranged in a regular pattern	Particles are arranged randomly	Particles are arranged randomly	**Arrangement** becomes more random (less regular)
Particles vibrate about their fixed positions	Particles move relatively freely in random directions	Particles move freely in random directions	**Freedom of movement** increases
Particles experience very strong attractive forces exerted by other particles	Particles experience strong attractive forces exerted by other particles	Particles experience weak (often negligible) attractive forces exerted by other particles	**Strength of attractive force between particles** decreases
Particles vibrate at high speeds	Particles move at very high speeds	Particles move at extremely high speeds	**Speed, kinetic energy** (KE = $\frac{1}{2}mv^2$) increases
Particles collide very frequently with neighbouring particles	Particles collide frequently with other particles	Particles seldom collide with other particles	**Collision frequency** increases

Tip

The kinetic particle model uses particles to represent either atoms or molecules.

- For example, in monoatomic gases (helium and other noble gases), one particle represents one gas atom.
- For example, in water (H_2O), oxygen (O_2) and carbon dioxide (CO_2), one particle represents one molecule and not an individual atom.

6. The kinetic particle model of matter is a *simplified general representation of reality* and *cannot explain some special cases* found in the real world. The following describes two exceptions.
   - According to the kinetic particle model, *density decreases when matter changes state from solid to liquid. Water is an important exception.* The density of water increases as ice melts into water. Thus, ice floats when placed in water. This unique behaviour is explained using chemical bonds in chemistry.

   - According to the kinetic particle model, *solids are denser than liquids. Mercury is an exception.* Mercury exists as a liquid at room temperature and has higher density than most solids. Thus, many solids float on it.

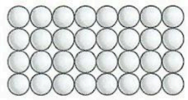
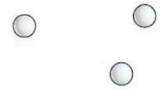
Metal nuts and glass marbles float on mercury.

Tip

The movement of students in school is a good analogy for the kinetic particle model.

	Solid	Liquid	Gas
Example	Students standing in orderly straight lines during school assembly.	Students moving along a crowded corridor.	A class of students playing a game of tag in the school.
Movement	Students can move only a little around their standing positions which is similar to the limited motion of solid particles.	The motion of students along a crowded corridor is similar to the flowing motion of liquid particles.	Students move constantly and rarely come in contact with each other. The distances between students are quite large too.

5. The table below shows how we can use the kinetic particle model to explain the different *physical properties* of the three states of matter.

2D Diagram of the Kinetic Particle Model for Each State of Matter	 solid	 liquid	 gas
Shape The appearance of the matter.	Solids have fixed shapes because the particles are held in fixed positions by strong attractive forces between the particles.	Liquids take the shape of the containers they occupy because the particles can move about relatively freely.	Gases take the shape of the containers they occupy because the particles can move about freely and randomly.
Volume The amount of space occupied.	Solids have fixed volumes at constant temperatures because the particles are held in fixed positions by very strong attractive forces between the particles.	Liquids have fixed volumes at constant temperatures because the particles are held close together by strong attractive forces between the particles.	Gases take the volume of the containers they occupy because the particles can move about freely and randomly.
Density The amount of substance packed into a fixed volume.	Solids have relatively high densities because the particles are closely packed together.	Liquids have relatively medium densities because the particles are loosely packed together.	Gases have relatively low densities because the particles are very far apart.
Compressibility The ease at which volume is reduced.	Solids are incompressible because there is very little space between the particles.	Liquids are (near) incompressible because there is very little space between the particles.	Gases are compressible because there is a lot of space between the particles.

Common Error

✗ Gases are compressible because their particles are soft and flexible. Solids are incompressible because their particles are hard and inflexible.

✓ The particles in the kinetic particle model are hard and have fixed shapes, even for gases. The solid, liquid or gas particles are not compressible.

Explanation

Gases are compressed purely by reducing the space between their particles. The volume of each individual particle does not change.

Worked Example 7.1

Liquefied natural gas (LNG) provided 95 percent of Singapore's energy needs in 2021. What is an advantage of liquefying natural gas?

A Less dangerous

B Less storage space needed

C More compressible

D Transports faster in pipes

Strategy

We start by eliminating the most unlikely option.

We eliminate option **C** because the state of liquid is less compressible than the state of gas.

We consider option **A** because it is unclear if the liquid state is less dangerous (less flammable) than the gas state.

We consider option **D** because it is not clear if the liquid state transports faster (flows faster) than the gas state.

We choose option **B** because we know the particles in the liquid state are spaced more closely than in the gas state.

Solution

B

Tip

In physics, you will come across terms such as law, theory and model.

- Newton's Laws of Motion is a set of patterns or rules which are followed by objects in motion. They are derived from observations and experiments.
- Theory of gravitational force is a way to describe why objects fall towards Earth. It is an attempt to explain an observed phenomenon using a concept or an idea.
- Kinetic particle model of matter is a way to represent atoms and molecules of matter. It simplifies and eases the understanding of reality.

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Checkpoint 7.1

1. When liquid mercury freezes, how do the mercury atoms change?

   A They are attracted more strongly to each other.

   B They move further away from each other.

   C They become smaller.

   D They become stationary.

Tip

Questions regarding the difference in properties of atoms in liquids and solids have appeared in examinations, e.g., N GCE N(A) Level Science Physics Sep/Oct 2021, Paper 1, Q10.

B Heating Increases Internal Energy

Learning Outcome

- Describe internal energy as an energy store which is the sum of:
  (i) the total kinetic energy of particles due to their random motion, and
  (ii) the total potential energy due to the forces between the particles in the system.

1. Heating a body will cause the body to either become warmer (the temperature increases) or melt/boil (the state of matter changes).
2. When you heat water in a kettle, its temperature increases and then it starts to boil.

   - Heating the water is a process of transferring energy to the water.
   - This transferred energy goes to the internal store of the water (i.e. internal energy increases).
3. In microscopic terms (using the kinetic particle model), **internal energy *U* is the sum of the total kinetic energy (KE) and total potential energy (PE) of the particles.**

   Internal energy U = total KE + total PE of the particles

4. *Heating the water increases* either the *total kinetic energy* or the *total potential energy of the water particles.*

	Initial Heating	Further Heating
Observation	water becomes hotter	water boils
Observed Change in the Physical Property of Water	temperature increases	state of matter changes
Change in the Energy of Water	internal energy increases	internal energy increases
Change in the Particles' Energy	total kinetic energy of particles increases	total potential energy of particles increases
Change in the Particles' Physical Property	particles move faster	particles are spaced further apart

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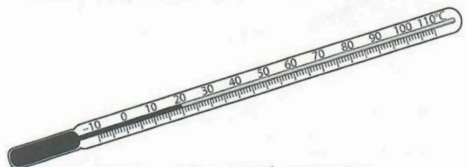
C Changes in Temperature and State of Matter

Learning Outcomes

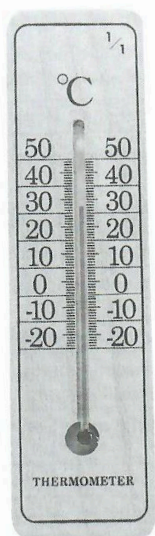
- Relate the rise in temperature of a body to the increase in average kinetic energy of the particles in the body.
- Describe the changes in the states of matter (melting/solidification and boiling/condensation) as processes involving energy transfer without temperature change.

1. Temperature is a measure of how hot or cold an object is.
   - The unit of temperature is degree Celsius (°C).
   - We can use a common laboratory thermometer to measure temperature in experiments.



Common laboratory thermometer

   - We can also use a common home thermometer to measure temperature at home.



   - Temperature is higher when it is hotter. Temperature is lower when it is colder.

Tip

The SI unit of temperature is kelvin (K) but it is not commonly used in daily life.

The temperature difference of 1 °C is equal to 1 K.

Temperature (in °C) = temperature (in K) + 273.15

2. When we heat water in a kettle, its temperature increases. The rise in temperature leads to the particles moving faster.

Heating of water
↓
Temperature of water increases
↓
Total kinetic energy of particles increases
↓
Average kinetic energy of particles increases
↓
Average speed of particles increases
(Overall, particles move faster)

3. When we heat the water further, it boils. The state of water changes from liquid to gas.

Further heating of water
↓
State of water changes from liquid to gas
↓
Total potential energy of particles increases
↓
Average spacing between particles increases
(Overall, particles are further apart)

4. Generally, when the state of matter changes, energy transfer occurs without a change in temperature.

Tip

- Generally, when particles under attractive forces are moved further apart, potential energy increases.
- Gravitational potential energy of an object (GPE = mgh) increases when height h increases (or distance between object and Earth's surface increases).
- Elastic energy of a spring increases when it is stretched more (or spacing between particles in the spring increases).

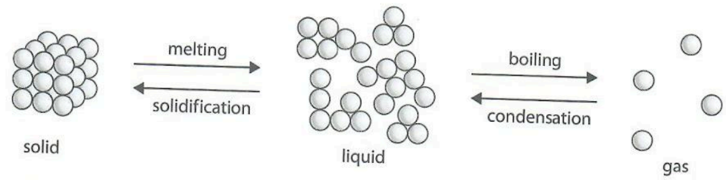
Common Misconception

✗ When you heat a substance, its temperature always increases.

✓ When you heat a substance, its temperature does not increase during melting or boiling.

Explanation
During a change in the state of matter, energy is put in to breaking the bonds that are holding the particles together. Potential energy of the particles increases and the particles move further apart.

5. We can use the kinetic particle model of matter to describe how the spacing and arrangement of the particles change during the changes of states. The diagram shows the arrangement of the particles in the three states of matter and how the arrangement changes from one process to another.



6. The change in state does not affect the speed of the particles. Hence, the average kinetic energy of the particles and the temperature of the matter remain the same.

The table summarises what takes place during the changes in the states of water.

Change in State	Transfer of Energy	Internal Energy	Total Potential Store of Particles / Average Spacing Between Particles	Total Kinetic Store of Particles / Average Speed of Particles	Temperature at Which Change in State Occurs
Melting	Transfer to matter	Increases	Increases	Unchanged	0 °C (melting point of ice)
Boiling	Transfer to matter	Increases	Increases	Unchanged	100 °C (boiling point of water)
Solidification	Transfer from matter	Decreases	Decreases	Unchanged	0 °C (melting point of ice)
Condensation	Transfer from matter	Decreases	Decreases	Unchanged	100 °C (boiling point of water)

Tip

Note that when changes in the states of matter (melting, boiling, solidification and condensation) occur, the mass of matter does not change (i.e. 1 kg of ice melts into 1 kg of water).

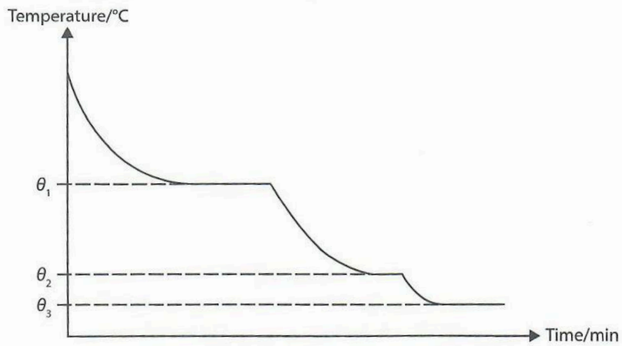
Tip

Evaporation is another process where matter in the liquid state changes to a gas. For example, after mopping the floor, the wet floor will eventually become dry. The water on the floor will evaporate and become water vapour.

Evaporation is different from boiling. Evaporation can happen at any temperature while boiling can only happen at the boiling point.

Worked Example 7.2

In an experiment, a sealed container of steam was cooled in a freezer. The graph shows the temperature changes in the container as it cooled.



(a) How does the state of matter change at temperature θ_1?

(b) How does the average kinetic energy of particles change from temperature θ_1 to temperature θ_2?

(c) How does the average spacing between particles change at temperature θ_2?

(d) What does temperature θ_3 represent?

Strategy

(a) Steam is the gaseous form of water. Note that a change in the state of a pure substance is characterised by the temperature remaining constant.

(b) Note that from temperature θ_1 to temperature θ_2, temperature decreases.

(c) Note that at temperature θ_2, solidification occurs.

(d) The water in the container will continue to lose energy to its surroundings until its temperature is the same as the surrounding temperature.

Solution

(a) Steam changes state from gas to liquid.

(b) The average kinetic energy of particles decreases.

(c) The average spacing between particles decreases.

(d) Temperature θ_3 represents the temperature inside the freezer.

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Checkpoint 7.2

1. A candle is melting.

   (a) How does the average spacing between the particles of the candle change?

   (b) How does the average speed of the particles of the candle change?

Test Station ▸▸

1. Which of the following does **not** take place in a substance during melting and boiling?
   - **A** Energy is transferred to the substance.
   - **B** The internal energy of the substance increases.
   - **C** The total potential energy of the particles in the substance increases.
   - **D** The forces of attraction between particles become stronger.
2. Which of the following takes place in a substance during solidification and condensation?
   - **A** The speed of the molecules decreases.
   - **B** The distance between the molecules decreases.
   - **C** The weight of the molecules decreases.
   - **D** The kinetic energy of the molecules decreases.
3. Figure 7.1 is an atomic-scale image of a surface obtained from the scanning tunnelling microscope (STM), which is widely used in both industrial and academic research.

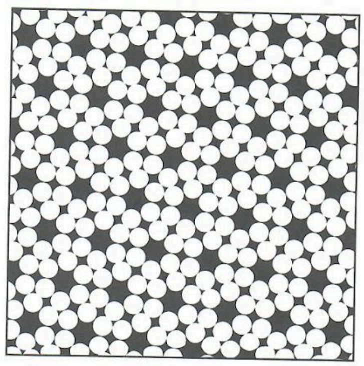

Figure 7.1

   (a) What is the state of matter shown in the image? [1]

   (b) Describe the motion of the particles shown in the image in terms of their freedom of movement. [1]

4. Table 7.1 shows the temperature readings of a thermometer in some ice that was heated over time.

Table 7.1

Time / min	0	1	2	3	4	5	6	7	8	9	10
Temperature / °C	0	0	0	5	25	45	65	85	100	100	100

   (a) Sketch the temperature–time graph using the readings given. [2]

   (b) Explain in terms of work done why the temperature of the ice remains constant in the first few minutes even though it is being heated up. [2]

5. The heat pump is commonly used in refrigerators and air-conditioning systems to produce cold air. Figure 7.2 shows a simplified model of how a heat pump works.

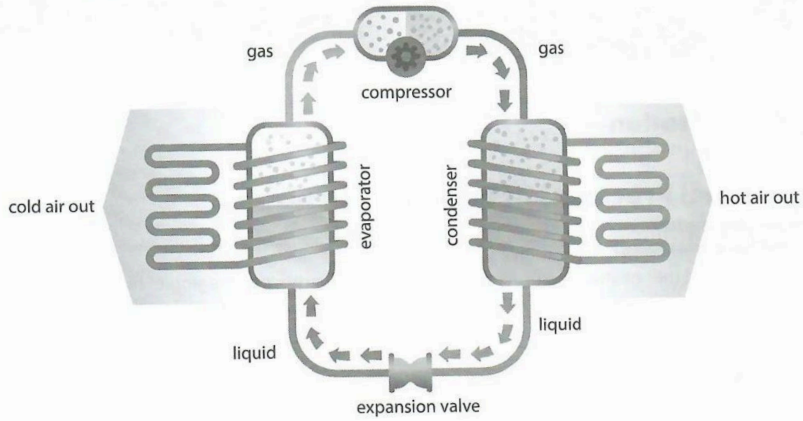

Figure 7.2

The condenser causes gas to become liquid while the evaporator causes liquid to become gas.

(a) Explain why hot air is produced near the condenser. [2]

(b) Explain why cold air is produced near the evaporator. [2]

(c) Explain how the heat pump can be used to transfer energy from the air in a refrigerator to the surroundings. [3]