5.4 The Kinetic Molecular Theory and Changes of State

Chemists know that they will probably never be able to observe exactly what is happening in a chemical reaction. Observation is a powerful tool of science, but it is limited to things that can be detected through the senses. Even with the best microscopes, X-ray machines, and MRI machines, the deepest nature of matter remains invisible. We are able to observe large-scale (macroscopic) changes; for example, when water is left in a glass for a period of time, it disappears through evaporation. But we cannot see the internal behaviour of water that causes the evaporation.

In Chapter 1, you learned how scientists develop theories to explain their observations. Many scientific theories are about changes inside matter, and scientific models are used to show what we cannot see. For example, to understand the evaporation of water, a model could use moving billiard balls or marbles, or even dots on paper, to provide an idea of what might be happening. The idea of tiny, invisible moving particles of water is a model that allows scientists to explain how water can leave a glass as a result of evaporation. A scientific theory, then, is an attempt to explain what is happening in the real world.

TRY THIS: What's in the Black Box?

Skills Focus: hypothesizing, predicting, conducting, inferring

"Imagination is more important than knowledge."

Albert Einstein

You may wonder how scientists know so much about the behaviour of matter if what happens inside matter is invisible. Science solves the mysteries of nature through a process that is much like a conversation between what you observe and what you think. What you observe prompts you to think of new ideas, and new ideas allow you to check for new observations. This activity is an opportunity to try the back and forth nature of this scientific conversation.

1. Your teacher will provide your group with a sealed "black box." Make a table like Table 1 to record your tests, observations, and ideas.

Table 1

Experimental test	Observation	Description

2. Examine the box and make some preliminary observations.
3. From these observations, conduct further tests to determine what is inside the box. Record your observations and a description of what you think is inside. For example, if it seems like something is rolling around inside the black box, you might test to see if it rolls on every side (then it could have a spherical shape), or if it only rolls on one side (then it could have a cylindrical shape). (Hint: Slow and gentle movement will likely give more information than rapid and random shaking.)
4. Repeat the process until you think you have completely described the inside of the box.
5. If time permits, try another box.

A. Compare your ideas about what is inside the box with the ideas of others who examined the same box. Do the others agree with you? If they do, does it make you right? If they don't, does this make them right and you wrong? Explain your thinking.

B. Would you like to know what the inside of the box really looks like? Nature never lets us look inside. What does this mean about what we can know?

C. What do you think makes scientists so sure about some models and not so sure about others?

The Kinetic Molecular Theory

The **kinetic molecular theory** is the idea that matter is made from moving invisible particles. This theory is used to explain the behaviour and changes in states of matter that we can observe. It takes ideas from our familiar world to describe the invisible nature of matter. The following principles make up the kinetic molecular theory:

- All matter is made up of tiny particles.
- Different substances have different particles.
- The particles are in constant motion.
- The more energy the particles have, the faster they move.
- The attraction between particles decreases with an increase in distance.

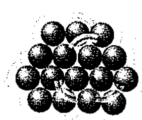
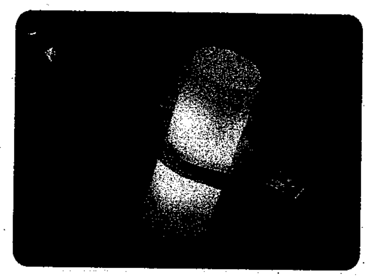
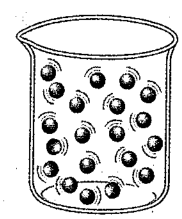
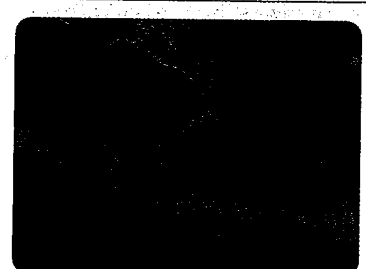
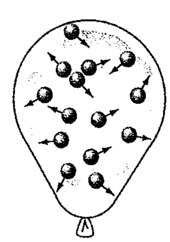
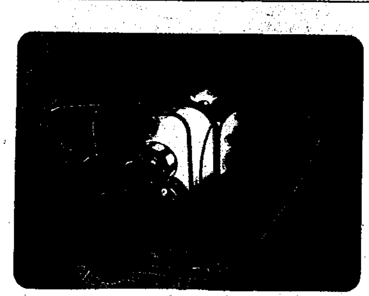
LEARNING TIP

Use Table 2 to explain to a partner the connections between the kinetic molecular theory and the states of matter. What do the visuals in the table show?

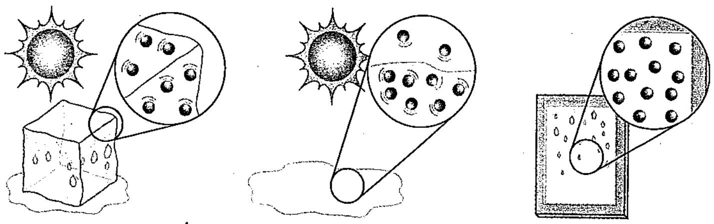
Explaining Changes of State

An important challenge for the kinetic molecular theory is to explain the states of matter and their changes in terms of the behaviour of particles. Does a theory of moving particles explain how substances can remain the same substance as they change from solids to liquids and gases, and back again? Table 2 shows the connections between this theory and the states of matter.

Table 2 The States of Matter and the Kinetic Molecular Theory

Solids **Distance:** particles close together **Type of motion:** particles can only vibrate in their place in the structure **Attractive Forces:** high, decreasing as vibrations get larger **Energy:** increasing energy causes an increase in vibration		
Liquids **Distance:** particles close together **Type of motion:** particles still vibrate, but can now move past one another; can bump into each other and the sides of their container **Attractive Forces:** still quite high, but less than solids and decreasing with distance apart **Energy:** increase in energy causes an increase in vibration and movement		
Gases **Distance:** particles very far apart **Type of motion:** particles vibrate, rotate, move past each other, and bump into each other in a very rapid straight line motion **Attractive forces:** no attractive forces; particles are too far apart and are moving too fast **Energy:** increase in energy causes an increase in pressure due to the increase in the speed and number of particles hitting the sides of the container		

Changing from one state to another is made possible by the addition or removal of energy. What we experience as heat, particles experience as motion. Any energy that enters a substance causes an increase in the movement of the particles, resulting in melting or sublimation in solids and evaporation in liquids. Cooling removes energy from a substance causing a reduction in the movement of the particles. This reduction in movement results in the condensation in deposition in gases and solidification in liquids (Figure 1).



(a) ice being heated **(b)** water being heated **(c)** water vapour being cooled

Figure 1 The addition or removal of energy changes the speed of particles and determines the state of the substance. In (a), the addition of energy (heat) causes melting. In (b), the addition of energy causes evaporation. In (c), the removal of energy causes condensation.

The motion of water molecules changes as heat is added or removed. If you heat solid ice, the water molecules begin to vibrate in place. As you apply more heat, the vibrations become so large that the molecules can now move past each other, resulting in liquid water. Applying more heat allows the water molecules to move even faster, overcoming the attractions between molecules and spreading out in three-dimensional space as fast-moving water molecules. We now have water vapour. If you remove heat from water vapour, the reverse process occurs. The water molecules slow down enough to allow the attraction between molecules to hold them together. Condensation occurs when enough heat is removed to cause molecules of water vapour to come together to form droplets of water. If you continue to remove heat from the liquid water, solidification occurs and the water changes to solid ice.

Explaining Dissolving and Density

The quality of any theory is judged by its ability to explain what we observe and to help us understand what is happening. The kinetic molecular theory can explain a great deal about dissolving. For example, sugar dissolving can be explained by particles of sugar being separated from the solid and entering spaces between particles of water (Figure 2). The kinetic molecular theory also explains the effects of hot water on the rate of dissolving. Since the warmer water particles are moving more quickly, they are capable of separating the sugar particles at a higher rate.

Changes in density, too, can be partially explained using the kinetic molecular theory. As substances are heated, the increased motion of the particles causes them to spread apart, resulting in an increase in volume, called expansion. For this reason, sidewalks, bridges, and railway lines are built with gaps to allow the solids to expand without cracking or buckling (Figure 3). Expansion also causes the liquid to rise in a thermometer.

Did You KNOW?

Flowing Land

Earthquakes can cause loose solids such as sand and gravel to flow like liquids. This process, called liquefaction, occurs when the sand and gravel particles vibrate enough to begin to move past one another and flow. Buildings can sink in the liquefied ground.

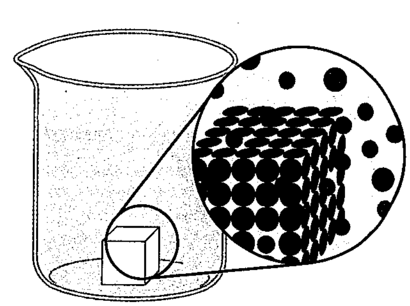


Figure 2 During dissolving, the particles of a solid are separated and distributed among the particles of the water.

Figure 3 Expansion joints in Lions Gate Bridge, Vancouver

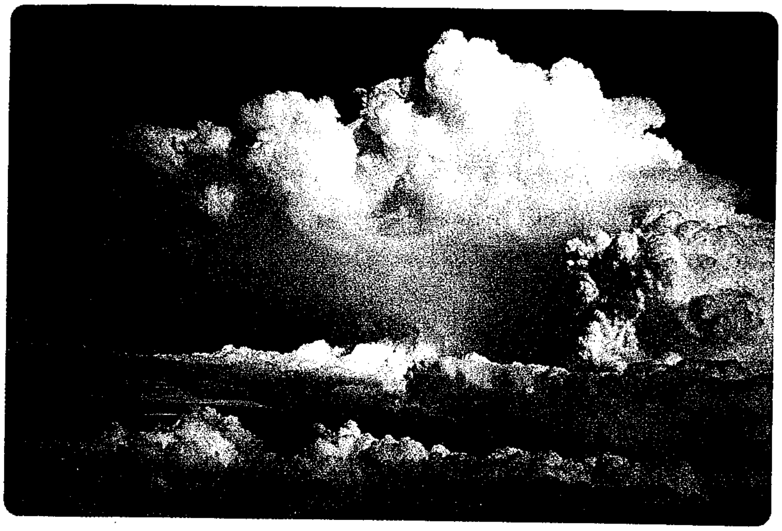


Figure 4 Cloud shapes often show how the air is rising and falling.

Since density equals $\frac{\text{mass}}{\text{volume}}$, when the volume increases and the mass stays the same, the density decreases. This is particularly important in liquids and gases and explains the rising of smoke and steam. Hot air particles are moving faster and have a greater volume (hence lower density) than the same mass of cool air (higher density). This explains why hot air rises or "floats" in cold air and; similarly, why cold water "sinks" in warm water. It is this change in particle motion when heat is added or removed that causes almost all of the weather on Earth (Figure 4).

TRY THIS: Topsy Turvy

Skills Focus: predicting, conducting, analyzing, inferring

Materials: 4 250 mL Erlenmeyer flasks (bottles will work as long as openings are the same size), red and blue food colouring, warm water, cool water, large pan or tray with lip, 2 3 × 5 cm index cards

In this activity, you will use what you know about the kinetic molecular theory to predict what happens when warm and cool water mix. Then, you will test your predictions.

Food colouring will stain clothing and skin.

1. Work with a partner. Add several drops of red food colouring to each of two 250 mL Erlenmeyer flasks. Fill them to the top with warm tap water (approximately 40 to 45 °C). Add several drops of blue food colouring to each of the other two 250 mL Erlenmeyer flasks and fill them to the top with cool tap water.
2. Predict what the outcome will be when one flask of warm water is inverted over one flask of cool water, and the water is allowed to mix. Predict the outcome when one flask of cool water is on top with one flask of warm water on the bottom.
3. Place one of the cool-water flasks in the pan. Place an index card on top of one flask filled with warm water. Invert the flask, holding the card in place. Stack it on top of the cool-water flask. Carefully remove the card (Figure 5) and, holding the flask, observe what happens when the water from both flasks mixes.

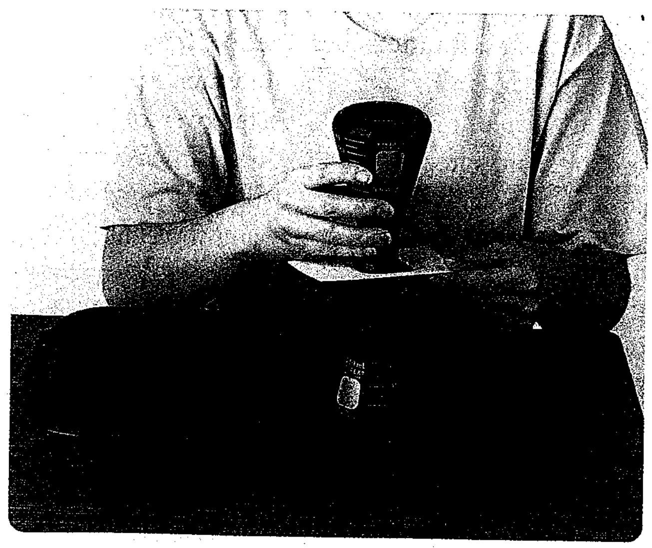


Figure 5

4. Repeat the inversion with a flask of cool water on top of a flask of warm water. Carefully remove the card, and observe.

A. Describe what happens when the warm water is on the top. Explain this in terms of the kinetic molecular theory.

B. Describe what happens when the warm water is on the bottom. Why do you think this happens when the warm water is on the bottom, not the top? Do you think the density of warm water is different from the density of cold water? Explain this in terms of the kinetic molecular theory.

5.4 CHECK YOUR Understanding

1. Where do the ideas for models and theories come from?
2. What must a scientific model be able to do?
3. How is a scientific model different from, for example, a model airplane?
4. Draw a table like Table 3 in your notebook. Complete the second column using terms from the following list: melting, evaporation, solidification, condensation, sublimation. Complete the third column by telling whether heat is added or removed to cause the change.

Table 3

State change	Name of change	Is heat added or removed?
solid to liquid		
solid to gas		
liquid to gas		
gas to solid		
gas to liquid		
liquid to solid		

5. Identify all the changes of state that are shown in the diagram in Figure 6. Describe what is happening to the water particles in each change.

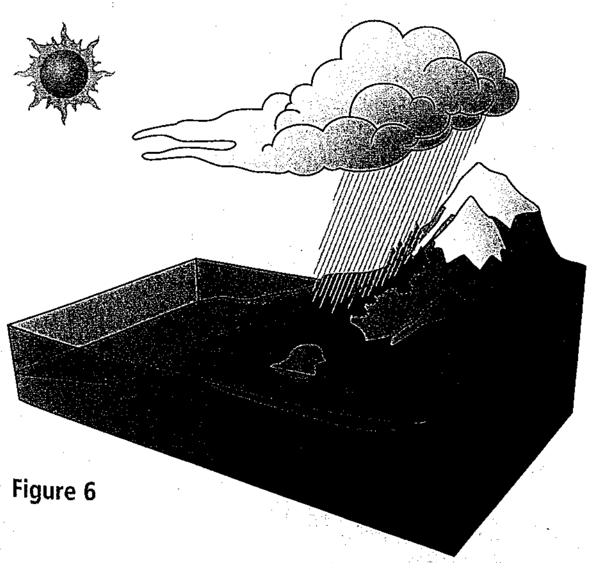


Figure 6

6. Figure 7 represents a beaker of water and a lump of sugar. Draw a sequence of two or three diagrams showing what happens to the particles of both substances as the sugar dissolves.

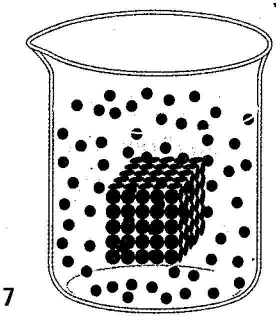


Figure 7

7. Frost forms when particles of water vapour come in contact with a very cold surface. Name this process and draw a representation of it. Give an example of where you might observe it.
8. Use the kinetic molecular theory to explain how stirring increases the rate of dissolving.
9. Which one of the three states of matter do you think can be compressed? What does this tell you about the spaces between particles in the three states?
10. A dented table-tennis ball can sometimes be "repaired" by immersing it in a pan of hot water. Explain how this works using a diagram to show how the change in the motion of the particles inside re-inflates the ball.
11. Explain how a drop of water on your desk can evaporate if the temperature of the room is 23 °C and the boiling point of water is 100 °C.
12. When gases are compressed, they must be placed in thick steel cylinders. Based on your understanding of the kinetic molecular theory, explain why this must be.
13. Roads, bridges, and railway tracks must be built with "expansion joints" to prevent bending and buckling during warm weather. Use the kinetic molecular theory to explain why expansion joints are necessary.