11.1 States of Matter and the Kinetic Molecular Theory

Figure 1 Liquid nitrogen can be used to remove warts.

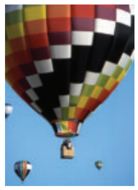
Have you ever had a wart removed? A wart is a non-cancerous skin growth caused by a viral infection. A wart can be "burned off" professionally by applying a small quantity of liquid nitrogen directly to the wart (**Figure 1**). Nitrogen is normally a gas at room temperature, having a boiling point of −196 °C. However, it can be liquefied if it is cooled below this temperature. As a result, liquid nitrogen is extremely cold—cold enough to instantly freeze the water in each cell of the wart. As the water freezes, it expands, causing the cells in the tissue of the wart to burst—much like a pop can that was left too long in the freezer. As the tissue is destroyed, the patient experiences a burning sensation in the affected area. The liquid nitrogen that was used in the procedure absorbs thermal energy from the wart and harmlessly evaporates to become nitrogen gas. This example illustrates how the three common states of matter are affected by the temperature of their surroundings.

In this section we will review the properties of these states and examine a useful theory that helps explain these properties.

States of Matter

There are three common states of matter: solid, liquid, and gas. Many of the differences between these states can be explained by considering the forces of attraction between entities (**Table 1**). Solids, for example, maintain their volume and shape. This suggests that the forces of attraction between the entities in solids are quite strong. Strong attractive forces also keep the entities in solids close together. This helps to explain why solids are difficult to compress.

Table 1 Three States of Matter

State	Properties	Model	Example
solid	• has definite shape and volume • is virtually incompressible • does not flow easily		
liquid	• takes the shape of the container but has a definite volume • is slightly compressible • flows readily		
gas	• takes the shape and volume of the container • is highly compressible • flows readily		

Liquids also maintain their volume. Unlike solids, however, liquids flow to take the shape of their container. Their ability to flow suggests that the forces of attraction in liquids are not as strong as in solids. Weaker attractive forces imply that the entities in a typical liquid are slightly farther apart than the entities in solids. The combination of weaker attractions and more space makes it easier for the entities to slide past each other as the liquid flows. This explains why liquids can flow and take the shape of their container. It also explains why liquids are slightly more compressible than solids. In Unit 1 you learned that the intermolecular forces of attraction in molecular substances are London forces, dipole–dipole attractions, and hydrogen bonds. Although these attractive forces are weak, their presence prevents liquids from vaporizing into gases.

Gases take the shape and volume of their container. For example, the stench of a partially decomposed banana in a locker quickly fills the school hallway when the locker is opened. Observations like these suggest that the attractive forces are very weak between entities in gases, and the distances between entities are great. This explains why gases are the easiest of the three states to compress (**Figure 2**).

In summary, many of the properties of solids, liquids, and gases can be explained by referring to the strength of the attractive forces between their entities. However, this explanation has its limitations. For example, it cannot explain why a fully inflated balloon shrivels when placed into liquid nitrogen and then expands when it is removed. It also cannot explain why the warmth of a room causes liquid nitrogen to evaporate. To complete our theoretical understanding of the states of matter we must also consider the motion of the entities in matter.

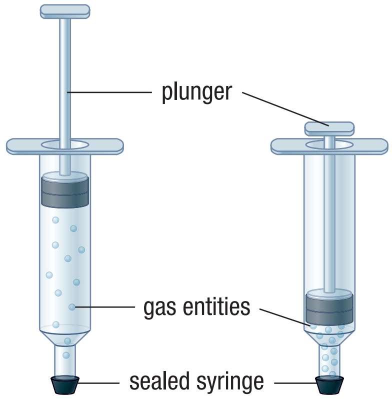


Figure 2 Gases are compressible: they can be squeezed so that they occupy a smaller volume. These two syringes contain the same number of gas entities.

Kinetic Molecular Theory

The aroma of cookies baking in the kitchen quickly fills an entire home. Why does this happen? One of the earliest clues to explain observations such as this came from the work of the Scottish scientist Robert Brown (1773–1858). Brown had been examining small specks of pollen suspended in water under the microscope. He observed that the pollen specks were moving in a random, zig-zag motion, as if they were being continually hit by invisible particles. This observed random movement eventually became known as **Brownian motion** (**Figure 3**).

Brownian motion the random movement of microscopic particles suspended in a liquid or a gas

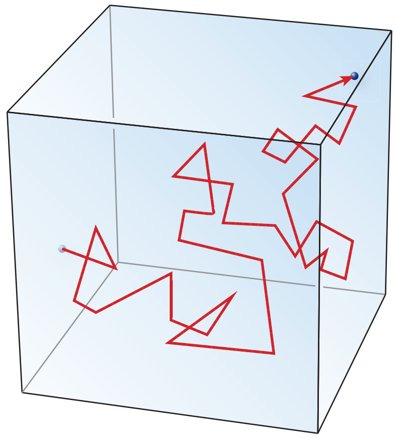


Figure 3 Brownian motion is the continuous random motion first described by Robert Brown.

Scientific interpretations of Brown's observations led to the development of the kinetic molecular theory. The main idea of the **kinetic molecular theory (KMT)** is that the entities in solids, liquids, and gases are in constant, random motion. As entities move about, they collide with one another and any other object in their path. The word "kinetic" comes from the Greek word *kinema*, meaning motion. The motion of these entities explains how the smell of baking cookies reaches your bedroom, some distance away from the kitchen. **Kinetic energy** is the energy of an entity due to its motion.

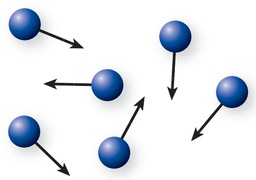
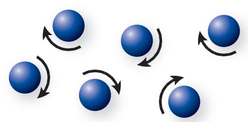
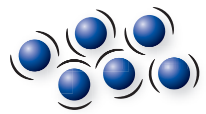
kinetic molecular theory the idea that all substances are composed of entities that are in constant, random motion

kinetic energy energy possessed by moving objects

How Entities Move

There are three ways in which the entities in matter can move: translational motion, rotational motion, and vibrational motion (**Table 2**). The type of motion in a sample of matter depends on the strength of the forces of attraction present.

Table 2 The Three Types of Motion

Translational motion	Rotational motion	Vibrational motion
• the movement of an entity through space along a linear (straight-line) path • in gases and liquids 	• the spinning of an entity in place • in gases and liquids • very limited in solids 	• the back-and-forth vibration of entities • in gases, liquids, and solids 

Strong attractions limit motion. The entities in most solids are therefore limited to vibrational motion. Strong attractions also result in a solid being the most ordered of the states of matter. Liquids exhibit all three forms of motion to some extent because their attractive forces are weaker than those in solids. That is also why the liquid state is less ordered than the solid state. For most practical applications, we may assume that there are no attractions between entities in a gas. As a result, the entities in gases exhibit all three forms of motion. Translational motion, however, is the most significant. Translational motion results in frequent, random collisions between entities in gases. Gas is the least ordered or most jumbled of the three common states of matter. **Table 3** compares the types of motion, strength of attractions, and degree of organization in the three states of matter.

Table 3 Types of Motion, Forces, and Organization of Entities in the Three States of Matter

	Solids	Liquids	Gases
Types of motion	vibrational	vibrational, rotational, and translational	vibrational, rotational, and translational
Strength of attraction	strongest	intermediate	weakest
Organization of entities	highly organized	intermediate level of organization	least organized

Kinetic Energy and Temperature

You now know that the entities in any substance are in constant motion and that the energy possessed by any moving object is called kinetic energy. When a substance is warmed, its entities move more rapidly. The entities in a solid, for example, vibrate back and forth because of their kinetic energy. As the solid is warmed, its entities remain fixed in their position but vibrate more rapidly. The faster these entities move, the greater their kinetic energy. The kinetic energy of the individual entities may vary but, on average, their kinetic energy increases as the solid is warmed. This increase in kinetic energy makes the substance feel warmer to the touch. **Temperature** is a measure of the average kinetic energy of the entities in a substance. When you measure the temperature of a substance with a thermometer, the entities of the substance collide with the glass of the thermometer. As the substance is warmed, these collisions become more energetic. This additional energy is then transferred to the liquid in the thermometer, causing the liquid to expand (**Figure 4**).

temperature a measure of the average kinetic energy of the entities of a substance

WEB LINK

There are online simulations that show molecular motion and its dependence on temperature. To investigate one of these simulations,

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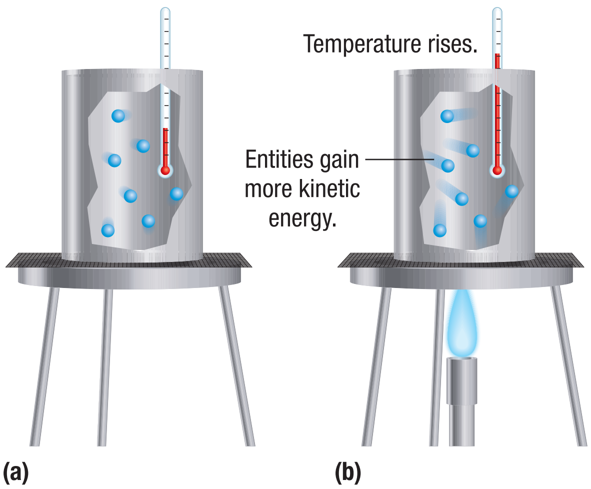

Figure 4 (a) Before heating, the entities have only a little kinetic energy. (b) After heating, they have much more kinetic energy and the thermometer indicates a higher temperature.

As more energy is transferred to a solid, its entities vibrate even faster. Eventually, the attractive forces between the entities are broken, allowing the entities to flow past each other. As a result, a change in state occurs in which the solid turns into liquid.

Warming a liquid also increases the kinetic energy of its entities. If sufficient energy is applied, the attractive forces between the entities in the liquid are completely overcome, allowing the liquid to boil and turn into a gas.

11.1 Summary

- The three common states of matter are solid, liquid, and gas. These three states have different properties, such as the ability to flow or be compressed.
- The kinetic molecular theory states that all substances contain entities that are in constant, random motion.
- Entities in a sample of matter may have translational motion, rotational motion, and/or vibrational motion, depending on their state.
- Entities in solid substances have limited motion, entities in liquids have an intermediate level of motion, and entities in gases have the most motion.
- Temperature is a measure of the average kinetic energy of the entities in a substance.
- As a substance is warmed, the kinetic energy of its entities increases, raising the temperature of the substance. If warming continues, some of the absorbed energy helps to overcome the attractive forces between the entities, resulting in a change of state.

11.1 Questions

1. Explain why solids have a definite shape and volume. K/U
2. Why are gases relatively easy to compress while solids are virtually incompressible? K/U
3. Rank the three common states of matter in order from least ordered to most ordered. How is this ranking related to the attractive forces between the entities in each state? K/U T/I
4. Why do gases and liquids flow, while solids do not? K/U
5. (a) What is the kinetic molecular theory (KMT)?
   (b) Use the KMT to explain the change illustrated in **Figure 5**.
   (c) Use the KMT to explain why the scent of perfume spreads more slowly outdoors in winter than it does in summer. K/U A

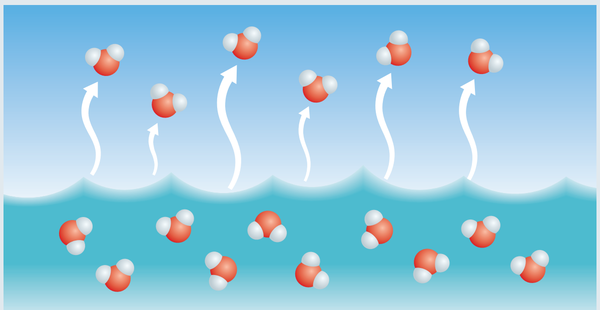

Figure 5

6. (a) How is temperature related to the motion of entities?
   (b) How does heating change the motion and temperature of the entities of a particular substance? K/U
7. Liquid nitrogen can be prepared by cooling and compressing air. Explain what happens to the molecules of nitrogen as it condenses. A
8. Propane is sold as a liquid in pressurized tanks. Use your knowledge of forces of attraction to explain what happens to liquid propane when it is released into the air in the burner of a propane barbecue. A
9. Dry ice is solid carbon dioxide. When exposed to room temperature, dry ice sublimates from a solid directly to a gas. Explain this change of state in terms of energy changes, molecular motion, and forces of attraction. T/I
10. Smoke is a mixture of tiny particles that are suspended in air. T/I A
    (a) Describe the motion of the particles of smoke moving from a smokestack through the atmosphere on a still day.
    (b) Would you expect particles of smoke to disperse faster in the summer or the winter? Explain your answer.
11. Why must car mechanics ensure that there are no air bubbles in the liquid in a vehicle's brake lines? To answer this question, you may need to research hydraulic brake systems. K/U A
12. Research one medical or industrial use of liquefied gases. T/I A
    (a) Briefly explain how the gas is liquefied.
    (b) Explain how the gas is used in this application.

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