SECTION 11.1

# Gases: Properties and Behaviour

**Key Terms**

kinetic molecular theory of gases
ideal gas

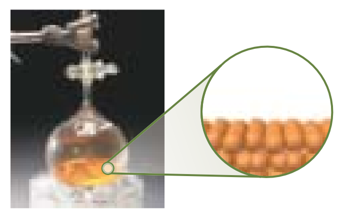
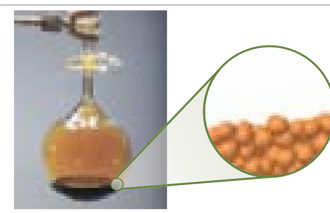
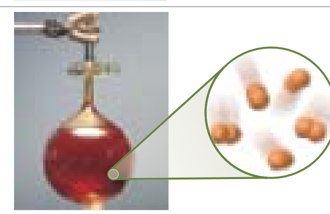
On Earth, matter typically exists in three physical states: solid, liquid, and gas. All three states of a substance are composed of particles (ions, atoms, or molecules). However, the behaviour of the particles differs in each state. These differences are summarized in **Table 11.1**.

Particles that make up a solid are packed tightly and closely together and are locked into place in an organized framework. This regular arrangement of the particles explains why solids have a fixed volume and shape—the particles are unable to move past one another to alter the shape.

Particles that make up a liquid are very close together, but they are not held in fixed positions. Therefore, they have no regular arrangement. As a result, particles of a liquid can move past one another, allowing the liquid to flow and take the shape of its container.

Particles of a gas are greatly separated from each other—much more so compared to particles in liquids and solids. Thus, particles of a gas have no regular arrangement. Gas particles move freely in all directions, bouncing off each other and the walls of any container in which they may be held.

**Table 11.1** Properties and Particles of the Three States of Matter

| State | Properties | Particles |
|---|---|---|
| Solid | • Constant shape<br>• Constant volume<br>• Almost incompressible | • Particles are organized in a regular pattern (this is also known as having "low disorder") and they vibrate in a fixed position.  |
| Liquid | • Variable shape<br>• Constant volume<br>• Almost incompressible | • Particles are less organized than in a solid and they are able to slide over and past one another.  |
| Gas | • Variable shape<br>• Variable volume<br>• Compressible (can be pushed or squeezed by a force to occupy a smaller volume) | • Particles are much less organized than in other states and they bounce off each other and the walls of their container.  |

## Changes of State and Forces between Particles

Two main factors determine the state of a substance: the forces holding the particles (ions, atoms, and molecules) together and the kinetic energy of the particles, which tends to pull them apart. If there were no forces between particles, all substances would be gases. Forces are necessary for particles to form liquids or solids. If the forces are very strong, a large amount of kinetic energy is needed to pull the particles apart. If the forces are weak, particles with smaller amounts of kinetic energy can pull away from one another. As shown in **Table 11.2**, the three types of forces that act between particles are attractions between oppositely charged ions, attractions between polar molecules, and attractions between non-polar molecules.

**Table 11.2** Attractive Forces That Influence the State of Matter

| | Type of Attractive Force | State of Matter | Example |
|---|---|---|---|
| Stronger Force | Between oppositely charged particles | Usually solid | Table salt, $NaCl(s)$ |
| | Between polar molecules | Solid, liquid, or gas | Glucose, $C_6H_{12}O_6(s)$<br>Ethanol, $CH_3CH_2OH(\ell)$<br>Ammonia, $NH_3(g)$ |
| Weaker Force | Between non-polar molecules | Solid, liquid, or gas | Paraffin, $C_{30}H_{62}(s)$<br>Pentane, $C_5H_{12}(\ell)$<br>Carbon dioxide, $CO_2(g)$ |

### Attractive Forces between Oppositely Charged Particles

Oppositely charged particles exert a pulling force on each other due to electrostatic attraction. Ionic bonding is an example of electrostatic attraction. In an ionic bond, a positive ion is attracted to a negative ion. Ionic bonds are very strong. As a result, ionic compounds usually exist as solids at room temperature.

### Attractive Forces between Polar Molecules

Attractive forces between polar molecules also occur. Although the overall charge of a polar molecule is neutral, one end of the molecule is partially positive and the other is partially negative. As a result, the polar molecule has a permanent dipole effect, as shown in **Figure 11.1**. Dipole-dipole forces between polar molecules are not as strong as ionic bonds. Thus, substances made up of polar molecules can exist as liquids and gases at room temperature. For example, ethanol is polar and exists as a liquid at room temperature. Hydrogen chloride is polar but is a gas at room temperature.

Hydrogen bonding is a specific type of dipole-dipole interaction. The strength of a hydrogen bond can vary, and this affects the state of a substance. For example, although water and ammonia are both polar molecules, the N–H hydrogen bonds in ammonia are less polar (and therefore weaker) than the O–H hydrogen bonds in water. Therefore, at room temperature, water is a liquid, while ammonia is a gas.

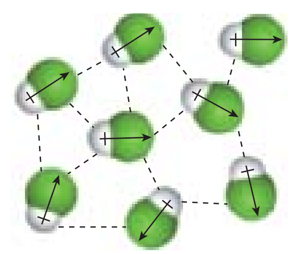


**Figure 11.1** In a polar substance such as hydrogen chloride, dipole-dipole forces of attraction exist between the molecules.

***Explain*** *Why do attractive forces occur between the different regions of these hydrogen chloride molecules?*

### Attractive Forces between Non-polar Molecules

Attractive forces exist between non-polar molecules due to the formation of temporary dipoles. However, these forces are weak. Most small non-polar molecules, such as carbon dioxide, do not hold together long enough to maintain a solid or liquid form at room temperature, so they exist as gases at room temperature. Larger non-polar molecules, such as pentane, $C_5H_{12}(\ell)$, are liquids at room temperature. As a non-polar molecule increases in size, the attractive forces between the molecules of a substance also increase. When the attractive forces between the molecules are strong, more energy in the form of heat must be added to weaken them before a change in state can occur.

### Learning Check

1. Using water as an example, name and distinguish between the three physical states of matter.
2. How is the state of a substance related to the attractive forces between its particles?
3. How is the state of a substance related to the arrangement of its particles?
4. Why would all substances be gases if there were no forces between particles?
5. Describe the relationship between the state of a substance and the kinetic energy of its particles.
6. Use a graphic organizer to distinguish the three types of forces between particles of substances.

## The Kinetic Energy of Particles and Temperature of a Substance

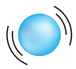


**Figure 11.2** This model of a particle depicts vibrational motion—the motion of something as it moves back and forth about a fixed position.

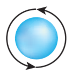


**Figure 11.3** This model of a particle depicts rotational motion—the motion of something as it spins on its axis.

**Figure 11.4** This model of a particle depicts translational motion—the motion of something that moves freely from one place to another.

If the particles of a substance had no kinetic energy but still had attractive forces between them, the substance would be solid. Particles must have kinetic energy to pull away from each other. Particles in a substance have three types of motion and thus three types of kinetic energy. **Figure 11.2** illustrates vibrational motion and thus vibrational kinetic energy. All particles, regardless of the state of the substance, have vibrational energy. **Figure 11.3** shows rotational motion and thus rotational kinetic energy. Particles in liquids and gases, and some solids, have rotational kinetic energy. **Figure 11.4** illustrates translational motion and thus translational kinetic energy. Only particles in liquids and gases can have translational kinetic energy.

The temperature of a substance is directly related to the average kinetic energy of its particles. To heat a substance means to add energy to the substance, which goes into the kinetic energy of its particles. As you heat a solid, the temperature increases and the particles vibrate more and more rapidly. Eventually, the particles will have enough energy to pull away from each other. However, they are still attracted to the nearby particles. Thus, in a liquid, particles are constantly sliding past one another. The strength of the forces determines how much energy is needed, and thus what the temperature must be, when particles pull away from one another.

As you heat a liquid, the temperature increases and all types of kinetic energy increase. Eventually, each particle will have enough energy to completely escape from all of the other particles in the substance as the substance becomes a gas. The strength of forces between particles determines how much energy must be added and thus what the temperature must be for the substance to become a gas.

## The Distinguishing Properties of Gases

Each state of matter has physical properties that distinguish that state from another state. The following properties distinguish gases from solids and liquids.

- *Gases are compressible*. The volume of a gas decreases greatly when pressure is exerted on the gas. Similarly, the volume of a gas increases when the pressure is reduced. In contrast, the volumes of liquids and solids remain almost constant during changes in pressure. The incompressibility of solids and liquids is explained by particles in these states being unable to move independently of each other. The movement of one particle affects the movement of the other particles. Gas particles, however, are able to move independently of one another.
- *Gases expand as the temperature is increased*, if the pressure remains constant. The volumes of liquids and solids can expand with increasing temperature as well, but to a much smaller extent compared to volumes of gases.
- *Gases have very low viscosity*. The viscosity of water is approximately 55 times greater than the viscosity of air. Air and all other gases flow through pipes more freely compared to liquids. The low viscosity of gases enables them to escape quickly through small openings in their containers.
- *Gases have much lower densities* than solids or liquids. The density of water vapour is approximately 1/1000 the density of liquid water.
- *Gases are miscible*. Substances that mix completely with each other are said to be miscible. All gases are miscible. Some liquids, such as water and alcohol, are miscible. Other liquids, such as water and oil, are *immiscible* (they do not mix).

## The Kinetic Molecular Theory of Gases

The **kinetic molecular theory of gases** provides a scientific model for explaining the behaviour of gases. To develop the theory, scientists defined a hypothetical substance called an ideal gas. An **ideal gas** is defined by specific characteristics related to the energy and motion of the gas particles, as shown in **Figure 11.5**. The kinetic molecular theory of gases is based on the following assumptions.

- Gas particles are in constant, random motion. Gas particles travel in straight lines until they collide with other gas particles or with the walls of their container. Therefore, an ideal gas has high *translational kinetic* energy.
- Individual gas particles are considered point masses. A *point mass* is a mass that has no volume—it takes up no space. The volume of an individual gas particle is considered negligible compared to the container holding the gas. Gas particles are considered to be extremely far apart and most of the container is thought of as empty.
- The gas particles do not exert attractive or repulsive forces on one another.
- The gas particles interact with one another and with the walls of their container only through *elastic collisions*. In an elastic collision—for example, when billiard balls collide—kinetic energy is conserved. Particles can exchange kinetic energy with one another in a collision but the total kinetic energy remains constant.
- The average kinetic energy of gas particles is directly related to temperature. The greater the temperature, the greater the average motion of the particles and the greater their average kinetic energy.

**kinetic molecular theory of gases** the theory that explains gas behaviour in terms of the random motion of particles with negligible volume and negligible attractive forces

**ideal gas** a hypothetical gas made up of particles that have mass but no volume and no attractive forces between them

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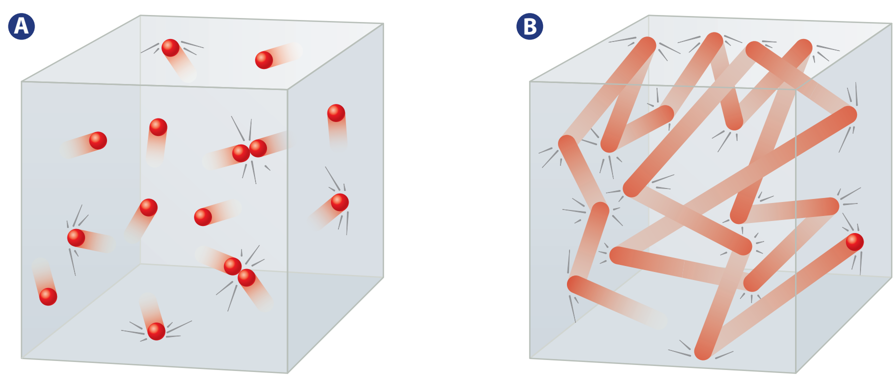



**Figure 11.5** Characteristics of ideal gas particles (molecules). In **(A)**, ideal gas molecules move with random motion, colliding with one another and with the walls of their container. In **(B)**, the paths of each individual molecule follow straight lines between collisions.

***Infer** how the kinetic molecular theory explains the increase of the volume of a gas with an increase in temperature, and make a sketch in your notebook to illustrate your ideas.*

Keep in mind that no gas is ideal. However, despite the fact that the kinetic molecular theory explains gases as if they were ideal, this important theory quite accurately describes the behaviour of real gases at ordinary temperatures and pressures. In fact, using the basic properties of an ideal gas, scientists can explain many properties of gases and can make accurate predictions about their behaviour under various circumstances and conditions. For example, the miscibility of gases can be explained by considering the large amount of space available between the molecules of a gas. The molecules of a second gas should fit readily into the spaces between the molecules of the first gas, because both types of gas molecules have negligible volume. Thus, two gases should mix evenly and completely as the molecules move about constantly. This predicted behaviour can be verified through observation.

## Section 11.1 REVIEW

### Section Summary

- Particles of matter behave in characteristic ways in each of the three states of matter. Attractive forces between particles and the kinetic energy of the particles influence how particles behave in each state.
- Attractive forces between particles that affect the states of matter are attractions between oppositely charged particles, attractions between polar molecules, and attractions between non-polar molecules.
- The properties that distinguish gases from liquids and solids include compressibility, low viscosity, even and complete mixing, low density, and expansion as a result of an increase in temperature.
- The kinetic molecular theory of gases is a model that explains the visible properties of gases based on the behaviour of individual atoms or molecules of an ideal gas.

### Review Questions

**1.** K/U What is the relationship between the strength of the attractive forces between the particles of a substance and the state of matter of the substance?

**2.** K/U How does the polarity of a molecule affect the state of a substance composed of that molecule?

**3.** C Draw a diagram that shows the attractive forces that occur for methanol, $CH_3OH$, and phosphine, $PH_3$. Based on these forces, identify the molecule that you predict would be a gas at room temperature, and explain why. (**Hint:** To draw methanol, the carbon atom is bonded to three hydrogen atoms and the oxygen atom. The fourth hydrogen atom is bonded to the oxygen.)

**4.** T/I Ammonia, $NH_3(g)$, is a gaseous compound with a boiling point of −33.34°C. Why is its boiling point substantially lower than the boiling point of water? Explain your answer.

**5.** K/U Describe two properties of matter in the solid or liquid state that distinguish it from matter in the gas state.

**6.** T/I A party balloon filled with helium gas is left to float in a room. Over time, the balloon falls back to the floor. Explain the behaviour of the balloon. (**Hint:** There are microscopic pores in the surface of the material that is used to make a party balloon.)

**7.** K/U For each property, explain how a gas differs from a liquid.

**a.** viscosity
**b.** compressibility
**c.** density
**d.** miscibility

**8.** A Identify a property of gases that is important in hot-air ballooning. Explain why you think it is important.

**9.** T/I Use the kinetic molecular theory to explain how a basketball is inflated.

**10.** A Which property of gases best explains each of the following situations? Explain your reasoning.

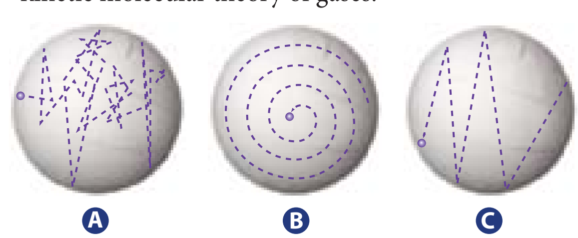
**a.** A full propane tank can provide enough fuel to run a propane barbecue for several months.
**b.** A carbon monoxide leak in the lower level of a building causes carbon monoxide gas to spread quickly throughout the whole building.
**c.** Forced air heating is often a better choice for home heating than hot water (radiator-type) heating.

**11.** A Hand pumps are often used to fill deflated bicycle tires with air. In a hand pump, a piston is pushed through a cylinder and air is transferred to the deflated tire. How do the properties of compressibility, low resistance to flow, and even and complete mixing relate to the inflation of tires?

**12.** K/U How does an elastic collision differ from an inelastic collision? To visualize an inelastic collision, imagine throwing a ball of putty against a wall.

**13.** K/U Describe the characteristics of an ideal gas. How do real gases differ from this hypothetical model?

**14.** T/I The images below show three possible paths for a gas molecule moving inside a filled volleyball. Which of these diagrams represents the most likely path of the gas molecule? Justify your choice in terms of the kinetic molecular theory of gases.




**15.** C Draw diagrams to show how the kinetic molecular theory can explain the following:

**a.** why a heated gas expands to fill its container
**b.** why gases can be easily compressed