How can we describe and explain the states of matter?

A skier pauses to take a drink of spring water, and then he breathes deeply. When he exhales, he will see small white puffs forming, similar to the clouds drifting above. Soon he will grab his poles and race down the hill, gliding along and carving into the snow and ice. The skier is experiencing water in all its forms: as a drinkable liquid, as a skiable solid, and as an invisible gas that he breathes in and out as part of the mixture we call air. Why does water in its different states—solid, liquid, and gas—have such different properties?

Key Concepts
- Matter can be solid, liquid, or gas.
- Matter is made of particles in constant motion.
- Changes in state result from changes in particle motion.
- The kinetic molecular theory explains physical changes and properties.

Curricular Competencies
- Make observations aimed at identifying your own questions about the natural world.
- Use scientific understandings to identify relationships and draw conclusions.
- Demonstrate an awareness of assumptions and identify bias in your own work and secondary sources.
- Communicate ideas using scientific language and representations.
CONCEPT 1

Matter can be solid, liquid, or gas.

Activity
What Is It?
Working in groups, add 250 mL of cornstarch into a large bowl. Feel the cornstarch with your hand. Then slowly add 85 mL of water and mix the cornstarch as you add the water. Mix the cornstarch with your hands so that you can feel the texture and consistency. Add some food colouring if you wish. Then experiment with the mixture. What happens when you grab a handful of the mixture and try to form a ball with it? Now open up your hand. What happens to the ball? Slap the cornstarch mixture quickly. Now try squeezing it. Is it a liquid? Is it a solid? How do you know?

Matter can exist as a solid, liquid, or gas. What are some examples of liquids and solids in your everyday life? Just this morning, you may have taken a shower in water and used some shampoo and conditioner on your hair: that’s three liquids. Perhaps you had a glass of juice or poured some milk on some cereal in a bowl and ate it with a metal spoon. That’s two more liquids and four solids. It can be hard to think of gases as matter because many gases are invisible. Although you cannot see them, gases surround us—you can feel gases filling your lungs every time you take a breath. Figure 2.12 describes examples of solids, liquids, and gases.

Figure 2.12 Kiteboarders depend on the different properties of solids, liquids, and gases to enjoy their sport. List three solids shown but not mentioned here and describe their physical properties.

Ocean water is a liquid mixture of water and dissolved salts. It also contains suspended solids such as grains of sand. Kiteboarders can skim along the surface of the water, or sink into it safely if the wind fails.

Air is a mixture of gases, including nitrogen, oxygen, water vapour, and carbon dioxide. The movement of air—wind—is what powers the kites.

The boards are made of solid materials that are strong and light.
Properties of the States of Matter

Solids, liquids, and gases have distinct characteristics that can be used to classify them. These characteristics are summarized below in Table 2.2.

Table 2.2 States of Matter

<table>
<thead>
<tr>
<th>State</th>
<th>Common Characteristics</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>solid</td>
<td>• holds its own shape</td>
<td>• wood</td>
</tr>
<tr>
<td></td>
<td>• has a constant volume</td>
<td>• silver</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• stone</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• plastic</td>
</tr>
<tr>
<td>liquid</td>
<td>• takes the shape of its container</td>
<td>• oil</td>
</tr>
<tr>
<td></td>
<td>• has a constant volume</td>
<td>• juice</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• antifreeze</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• gasoline</td>
</tr>
<tr>
<td>gas</td>
<td>• takes the shape and volume of its container</td>
<td>• air</td>
</tr>
<tr>
<td></td>
<td>• can be compressed</td>
<td>• helium</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• hydrogen</td>
</tr>
</tbody>
</table>

The Fourth State

Solids, liquids, and gases are the most familiar states of matter. But most matter in the universe actually exists as a fourth state of matter called plasma. A plasma is similar to a gas in that it does not have a defined shape and volume, but plasmas have different electrical properties than gases. Some examples of plasmas are shown in Figure 2.13.

![Figure 2.13](image)

Before you leave this page...

1. Give two examples of solids, liquids, and gases.
2. Which state of matter does plasma most resemble and why?
CONCEPT 2
Matter is made of particles in constant motion.

Activity
Musing on Models
What does the term "model" mean to you? Write a brief definition. What are some different examples of models in everyday life? How do you think models are used in science?

model a verbal, mathematical, or visual representation of a scientific structure or process

theory a scientific explanation that has been supported by consistent, repeated experimental results and is therefore accepted by most scientists

The terms "model" and "theory" have a variety of different meanings in different contexts. In science, however, they have very specific meanings.

A model consists of words, pictures, physical objects, or mathematical equations that are used to represent and explain complex objects, living things, or events in nature. Models help people analyze and communicate what they observe in the natural world. They also help us visualize processes that cannot be seen with the unaided eye. Some examples of models are shown in Figure 2.14.

A scientific theory is an explanation of a phenomenon in the natural world based on many observations and investigations. Theories can be, and often are, modified or discarded if new experimental data arise that contradict the theory or that the
theory cannot explain. Theories often lead to new conclusions. A theory is considered successful if it both explains experimental observations and can be used to make accurate predictions. A theory is never considered to be proven, no matter how successful it is. Future experiments may lead to further changes.

**Explaining Properties of the States of Matter**

The particle model of matter is a model that enables people to visualize and understand the structure of matter, even though we cannot see it. According to the particle model of matter, all matter is made up of very small particles. These particles are so small that they cannot be seen even with the help of a light microscope.

Using the particle model of matter, scientists developed a theory to explain the behaviour of gases. This scientific theory, when extended to explain the behaviour of all states of matter, is called the kinetic molecular theory of matter (KMT). An important part of the kinetic molecular theory of matter is the notion of kinetic energy—the energy of motion. According to the theory, all particles are constantly moving and therefore have kinetic energy. The kinetic molecular theory successfully explains many observations about matter, including the different properties of the states of matter, as well as the ways in which matter changes state.

**The Kinetic Molecular Theory of Matter**

The key points of the kinetic molecular theory of matter are:

1. All matter is made up of very small particles.

2. The particles exist in empty space.
   
   (a) In solids, particles are closely packed and held rigidly in place.
   
   (b) In liquids, particles are also closely packed but can move around.
   
   (c) In gases, particles have large amounts of empty space between them and are not attracted to one another.

3. Particles are constantly moving.
   
   (a) The particles in solids vibrate but cannot move around.
   
   (b) The particles in liquids slip and slide past and revolve around each other but stay close together. They collide with each other and the walls of their container.
   
   (c) The particles in gases move freely in straight lines, colliding with each other and with the walls of their container.

4. Energy makes particles move. The more energy the particles have, the faster they can move and the farther apart they can get.
States of Matter and the Kinetic Molecular Theory

To use the kinetic molecular theory as a tool for explaining observations about the states of matter, it can help to visualize the particles for each state, as shown in Figure 2.15. Note that the particles in a gas are actually much farther apart than is suggested by the diagram.

Particles in a Solid
- very close together
- vibrate but do not move around
- attract one another strongly in a rigid structure

Particles in a Liquid
- very close together
- slip and slide past and revolve around one another
- attract one another less strongly than in solids

Particles in a Gas
- very far apart compared to their size
- move randomly and quickly in straight lines
- attraction to one another is effectively zero

Before you leave this page . . .

1. In what ways does a model differ from a theory?
2. Summarize the kinetic molecular theory of matter.
3. Describe the particles of the three states of matter in terms of how they move and the spaces between them.
4. It is easy to compress (reduce the volume of) a gas, but solids and liquids cannot be compressed very much. Use the KMT to explain why.
CONCEPT 3
Changes in state result from changes in particle motion.

Activity
The Cold Can
Dry the outside of a metal can with paper towel. Obtain 50 g (about 45 mL) of salt. Divide it into three approximately equal portions. Add the first portion of salt to the can, then half-fill the can with crushed ice. Add the second portion of salt and fill the can with ice. Top with the rest of the salt. Mix the contents well, being careful not to spill the contents of the can. Wait 5 minutes and observe the outside and inside of the can. How do you explain what you observe?

Changes of state (also referred to as phase changes) occur when matter transforms from one state to another. Most pure substances can exist in all three states depending on the temperature and pressure. A few substances, such as water, exist in all three states under ordinary conditions on Earth. Scientists use specific terms to refer to the different state changes that are possible among solids, liquids, and gases, as shown in Figure 2.16.

Figure 2.16 Specific terms such as melting and evaporation are used to describe how the state of matter can change.
Changes of State and Temperature

What causes matter to change from one state to another? Consider what is the same about the following examples. You put a scoop of solid butter in a hot frying pan and it melts into a liquid. A kettle full of water begins to "sing" as the heating element inside causes the water to boil. You drop some ice cubes into your orange juice and they begin to melt. You fill the empty ice cube tray with water and pop it in the freezer to make more ice. All of these examples involve adding or removing kinetic energy.

Adding energy to matter or removing energy from matter changes the temperature of the matter. What does that mean? Temperature is a measure of the average kinetic energy of the particles in a substance. Increasing the temperature of matter means the particles of the matter are gaining energy. Once the matter reaches a certain temperature, the particles have gained enough energy to change state.

The temperature at which a substance melts is called its melting point. The temperature at which a substance boils is called its boiling point. The melting and boiling points of pure substances are physical properties that can be used to identify them. A few examples are shown in Table 2.3.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Melting Point (°C)</th>
<th>Boiling Point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>nitrogen, N₂</td>
<td>-210.0</td>
<td>-195.8</td>
</tr>
<tr>
<td>mercury, Hg</td>
<td>-38.8</td>
<td>356.7</td>
</tr>
<tr>
<td>water, H₂O</td>
<td>0.00</td>
<td>100.0</td>
</tr>
<tr>
<td>iron, Fe</td>
<td>1538</td>
<td>2862</td>
</tr>
</tbody>
</table>

The Kinetic Molecular Theory and Changes of State

The difference between the properties of solids, liquids, and gases can be explained by the difference in the kinetic energy of the particles of substances in those states. For any given substance, the average kinetic energy of the particles in the solid will be lower than that of the particles in the liquid. The particles in the gas will have the greatest average kinetic energy.

But why do substances change from one state to another when they are heated or cooled? Why does a heated solid melt instead of just becoming a very hot solid? Figure 2.17 shows how the KMT explains changes of state.
Adding Energy to Mercury

1. Solid mercury
   Particles are very close to one another, are fixed in position, and vibrate. They strongly attract one another.

2. Melting mercury
   As the temperature of the solid mercury increases, the kinetic energy of the particles increases. Eventually, the increased kinetic energy of the particles allows them to partially overcome their attraction to one another, and they break free of their rigid formation. They now begin to revolve around and slide past one another. The solid is melting.

3. Liquid mercury
   The particles move freely around one another, but are still close together and strongly attracted. They have taken the shape of their container.

4. Boiling mercury
   As the temperature continues to increase, the kinetic energy increases and the particles move more vigorously. Some particles gain enough energy to completely overcome the attractive forces between them and other particles in the liquid. They escape into the surrounding air.

5. Gaseous mercury
   All particles are highly energetic and move freely to fill their container. Further heating will increase the speed of the gas particles, which increases their kinetic energy. If in a sealed container, particles will collide with each other and with the walls of the container more forcefully and more often. This increases the pressure of the gas.

Extending the Connections
Applying Deposition
The metallic colours of modern electronics such as phones are due to specialized materials applied using physical vapour deposition (PVD). Research PVD and choose one specific application to explore.

Figure 2.17 As a sample of solid mercury absorbs energy (shown by the orange arrows), it undergoes two changes of state.

Before you leave this page . . .

1. Define temperature.
2. What is the melting point of a substance?
3. Use the KMT to explain how a liquid changes into a solid.
CONCEPT 4
The kinetic molecular theory explains physical changes and properties.

Activity
Dye-ing to Dissolve
Work in groups. Your teacher will give you two dye tablets of the same colour. Fill one beaker with 250 mL of cold tap water and a second beaker with 250 mL of hot tap water. Place one tablet in each beaker. Record your observations using words and diagrams or photos. Do not stir the mixtures. In your group, come up with a way of communicating your findings. Share and discuss your results as a class.

The kinetic molecular theory explains states of matter and changes of state, but it can also be used to explain other physical changes as well as physical properties. For example, think about what happens when a solid dissolves in a liquid. If you place a sugar cube in water, it will appear to get smaller and smaller as time passes. Soon it will seem to disappear. If you tasted the water, however, it would taste sweet. This is evidence that the sugar has not disappeared but is still present in the liquid. A solution of water and sugar has formed. As shown in Figure 2.18, the kinetic molecular theory can help explain what happened.

Explaining Diffusion
Have you ever come home and instantly known what was for dinner just by the smell? The spreading of smells is an example of diffusion—the movement of one material through another. Why and how does the smell of fried onions or toasted bread travel from their sources to your nose? Odours come from gases that have characteristic smells. During cooking, those gases are released. Because gas particles move freely and quickly, those particles spread throughout the room.

Figure 2.18 Kinetic molecular theory can help you visualize and explain what is happening to a sugar cube as it dissolves. Why does sugar dissolve faster in hot water?
Explaining Thermal Expansion

Solids, liquids, and gases normally expand when they are heated, and contract when they are cooled. This means that the hotter most substances get, the more their volume increases. The colder they get, the smaller their volume. The expansion of heated materials is called thermal expansion.

In places such as British Columbia, where temperatures can range from very cold to very hot, engineers must consider thermal expansion when building bridges and other structures. Repeated expansion and contraction can weaken building materials such as concrete, which can cause buckling, cracks, and breaks. Expansion joints such as the one shown in Figure 2.15 allow materials to expand and contract as the temperature changes without damaging the overall structure.

Why do materials expand when they get hotter? What is happening to the particles of those materials?

- Heating a solid increases the kinetic energy of its particles, which causes them to vibrate faster. This increase in vibrational motion causes the particles to move slightly farther apart, and the material as a whole expands. The same thing happens in liquids and gases. Added energy increases their motion, and the particles move farther apart.

- Liquids expand more than solids, because their particles move more freely and can move farther apart from one another.

- Gases can expand indefinitely, but gases heated in rigid containers cannot expand more than the walls of their containers allow. The particles collide with greater and greater force with the container walls, which means that the pressure on the inside of the container increases. If the pressure becomes great enough, the container will explode.

Before you leave this page...

1. Use KMT to explain why a balloon in a hot car will expand and may eventually pop.
2. Use the KMT to explain what happens when salt dissolves in water.
3. The thermometers you use in the lab likely contain a narrow column of red-dyed alcohol. Use the KMT to explain how this type of thermometer works.
4. What might happen if a bridge were built in B.C. without an expansion joint? Explain.