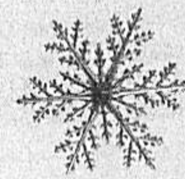
2.1 Properties of Matter

Warm Up



1. List four properties of snow.

   ____________________ ____________________

   ____________________ ____________________

2. Name or describe two different types of snow.

   ____________________ ____________________

3. Suggest why there are different types of snow. Hint: Think about why snow can have different properties.

   ____

Classifying Material Properties

Chemistry is the science concerned with the properties, composition, and behaviour of matter. **Matter** is anything that has mass and occupies space. **Mass** is the amount of matter contained in a thing. Usually the mass of common things is measured in grams (g) or kilograms (kg).

Properties are the qualities of a thing, especially those qualities common to a group of things. The relationship between matter and its properties is a very important aspect of chemistry. Properties are classified as being extensive or intensive.

Extensive properties are qualities that are or depend on the amount of the material. Examples of extensive properties are mass, volume, the electrical resistance of a copper wire (which depends on its diameter and length), and the flexibility of a metal sheet (which depends on its thickness).

Intensive properties are qualities that do not depend on the amount of the material. Melting point and density are examples of intensive properties. The gold in Figure 2.1.1 has a melting point of 1064°C and a density of 19.3 g/cm^3. Put another way, gold's melting point and density are the same for all samples of gold. These properties can therefore be used to identify that material. Other intensive properties such as temperature, concentration, and tension differ from sample to sample of the same material.

Figure 2.1.1 *Gold's melting point and density are two intensive properties that can be used to identify samples.*

Every material possesses a unique set of intensive properties that can be used to identify it.

You may be familiar from previous science courses with the alchemist's four elements of matter: earth, air, fire, and water. These elements were not equivalent to matter in modern chemistry. For the alchemists, earth, air, fire, and water represented four fundamental properties of matter. Alchemists believed that these properties existed independent of matter and could be added to matter or removed from matter to transform it. In other words, the alchemists had it backwards: they believed that a material depends on its properties rather that the properties depending on the material.

Physical Properties versus Chemical Properties

The properties of matter are also classified as being either physical properties or chemical properties. **Physical properties** describe physical changes, which are changes of state or form. Physical properties also describe the physical characteristics of a material. **Chemical properties** describe chemical changes. Chemical changes are those in which a new substance(s) or species is formed (Figure 2.1.2). Chemical properties also describe the tendency of a chemical to react. Chemical properties describe relationships or interactions between different forms of matter. They include a chemical's stability, its reactivity with other chemicals, its toxicity, and its flammability.

Most physical properties describe relationships or interactions between matter and energy. A material's electrical properties, magnetic properties, thermal properties, optical properties, acoustical properties, radiological properties, and mechanical properties (various indicators of strength) are all classified as physical properties. For example, a material can be classified as opaque, transparent, or translucent by how it interacts with light. Other physical properties you may have learned about include temperature, density, viscosity, and surface tension. In this section we'll focus on thermal properties (those related to thermal energy and heat).

Physical properties describe physical changes. Chemical properties describe interactions between different forms of matter.

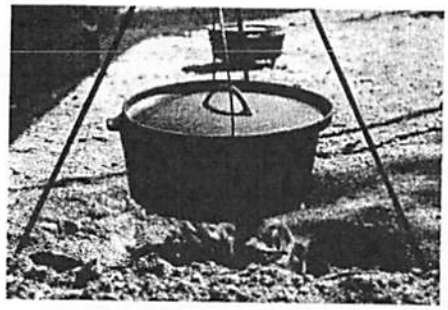


Figure 2.1.2 *The wood that is burning to heat the pot is undergoing chemical changes. The boiling soup in the pot is undergoing a physical change.*

Particle Relationships

Matter is composed of basic units or particles that move independently. In some forms of matter, these particles are atoms while in others these particles are groups of atoms called molecules or polyatomic ions. Physical changes involve the rearrangement of a material's own particles. Chemical changes involve the reorganization of two or more substances' atoms in relation to each other.

Physical properties depend solely on the relationships between the material's own particles. Chemical properties depend on the difference between the atoms' current relationships with other atoms and new relationships with different atoms. For molecular substances, physical changes alter intermolecular relationships (those between the molecules) while chemical changes alter intramolecular relationships (those within molecules). Physical changes generally involve less energy than chemical changes. Changing the positions of molecules relative to one another involves less energy than changing the positions of atoms within molecules. Nature forms hierarchies or levels of organization. Subatomic particles (protons, neutrons and electrons) form atoms which in turn may form molecules which in turn form materials.

Quick Check

1. What is matter?

2. What is a property?

3. What is an extensive property?

4. What is a chemical property?

Kinetic Energy

Kinetic energy is any form of energy that cannot be stored. The greater an object's speed and mass, the greater its kinetic energy. The particles of matter possess a type of kinetic energy called **mechanical energy** because of their continuous motion. Independent atoms and molecules have three forms of mechanical energy or types of motion: translational (movement from place to place), rotational (movement about an axis), and vibrational (a repetitive "back and forth" motion).

Thermal Energy, Temperature, and Heat

Thermal energy is the total mechanical energy of an object's or a material's particles. It is an extensive property as it depends on the size of the object or the amount of the material. Within any substance there is a "normal" distribution of kinetic energy among its particles due to their random collisions. This is very similar to the "normal" distribution of marks among the members of a class. **Temperature** is the average mechanical energy of the particles that compose a material and is therefore an intensive property. An increase in a material's temperature indicates that the average speed of its particles has increased.

A bathtub full of cold water has more thermal energy than a cup of boiling water because the bathtub contains so many more molecules even though they are moving more slowly. Consider the following analogy. Which contains more money, a bathtub full of $5 bills or a cup full of $20 bills? Despite the greater denomination of the bills in the cup, the bathtub still contains more money because it contains so many more bills.

A physical property is largely defined by the instrument used to measure it. Thermometers are used to measure temperature. There are many kinds of thermometers. All thermometers work by correlating some other property of a material to its temperature. Some electronic thermometers contain a small semiconductor, the electric resistance of which correlates to its temperature. Some medical thermometers contain liquid crystals that change colour with varying temperature. Some thermometers correlate the temperature of a material to the infrared radiation it emits. Scientists can infer the temperature of luminous materials from the visible light the materials emit. The standard laboratory thermometer uses the expansion of a column of liquid, usually tinted alcohol or mercury, as an index of its temperature. As a natural consequence of moving faster, the thermometer's particles (atoms or molecules) strike each other harder and spread farther from each other. The expansion of the thermometer fluid is proportional to the average kinetic energy of its particles.

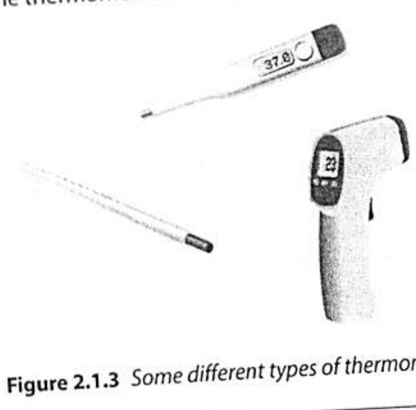


Figure 2.1.3 *Some different types of thermometers*

Most thermometers, including the standard laboratory thermometer, actually display the temperature of the thermometer itself rather than that of the fluid it is immersed in. The scientific definition of **heat** is the energy transferred from one body to another because of a difference in temperature. An object immersed in a fluid will transfer or exchange thermal energy with the fluid until both arrive at the same temperature thus the thermometer ultimately becomes the same temperature as the fluid it is immersed in. This however introduces a "Catch-22" into measuring temperature: the thermometer can't measure the temperature without altering it. When a cold thermometer is placed into hot water, the thermometer heats up and the water cools down until they are at the same temperature. For this reason, chemists include thermometers in their apparatus at the beginning of experiments so they will not have to introduce them into the fluid later.

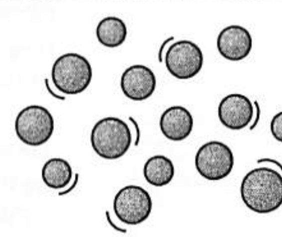
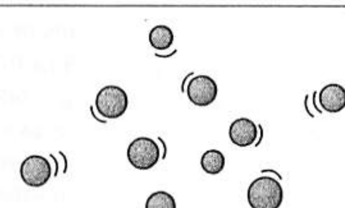
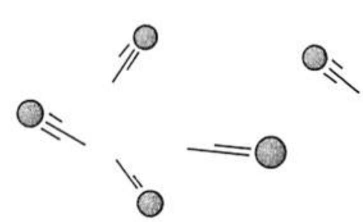
Quick Check

1. What is temperature? ______________________________
2. What is thermal energy? ______________________________
3. What is heat? ______________________________

The States of Matter

Under normal conditions, matter exists in three states: solid, liquid, or gas. The three states can be defined using both an operational definition and a conceptual definition as in Table 2.1.1. An **operational definition** consists of observable characteristics that help us classify things as belonging or not belonging to the defined group. **Conceptual definitions** explain what operational definitions describe.

Table 2.1.1 *The States of Matter*

State	Operational Definition		Conceptual Definition
	Shape	Volume	
solid	fixed	fixed	Each particle bounces around pushing the ones surrounding it outward. The particles have not spread far enough apart for any particle to fit through a gap between the particles surrounding it so the structure remains intact. 
			
liquid	adopts its container's	fixed	The particles are travelling faster and striking each other harder. As a result they have spread apart to an extent where they can slip by one another. 
			
gas	adopts its container's	adopts its container's	The particles have been struck with enough force to escape their attractions to the other particles in the liquid. They are now either too far apart or moving too fast for their attractions to affect their movement. 
			

The Kinetic Molecular Theory

The **kinetic molecular theory** explains what happens to matter when the kinetic energy of particles changes. The key points of the kinetic molecular theory are:

1. All matter is made up of tiny particles.
2. There is empty space between particles.
3. Particles are always moving. Their freedom to move depends on whether they are in a solid, liquid, or gas, as described in Table 2.1.1 above.
4. The particles move because of energy. The amount of energy the particles have determine how fast the particles move and how much or far they move.

Figure 2.1.4 identifies the three states of matter and the terms for each phase change. These phase changes depend on temperature. The following terms describe changes from one state to another.

- **freezing:** liquid to solid
- **melting**: solid to liquid
- **evaporation** (also known as vaporization): liquid to gas
- **condensation**: gas to liquid
- **sublimation**: solid to gas
- **deposition**: gas to solid

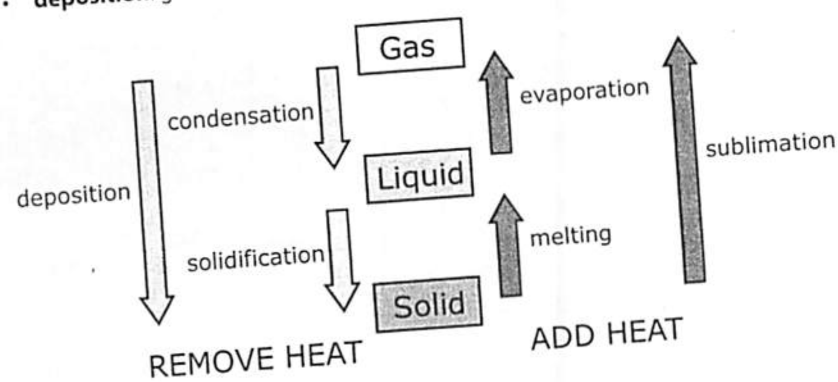


Figure 2.1.4 *Changes of state*

Quick Check

1. Explain the difference between the operational and conceptual definition of a liquid.
2. Describe the differences in kinetic energy between the particles in a cube of ice and a glass of water.
3. How does heat contribute to a phase change?

Melting Point

A material's **melting point** is the temperature of its solid as it changes to a liquid. Melting occurs because the independent particles (atoms, molecules, or ions) have spread far enough apart so that they can just slip through the gaps between the atoms surrounding them. The melting point of a substance depends on the strength of the attractive forces (bond strength) between its independent particles as well as the mass and symmetry of the particles. The freezing point and melting point of most substances are the same. Thus, the melting point may also be described as the temperature at which a solid can be immersed indefinitely in its own liquid because its rate of melting equals its rate of freezing.

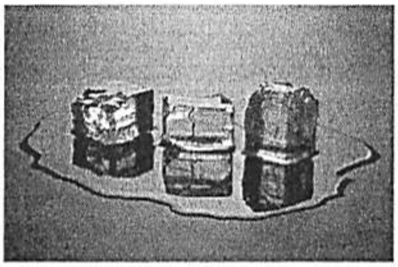


Figure 2.1.5 *At the melting point, a substance can exist in both the solid and liquid states.*

Boiling Point

Boiling is a special case of evaporation. Any particle in the liquid state may evaporate. The puddles on your street evaporate but you've never seen a puddle boil. The gas formed by a substance that boils above room temperature is called **vapour**.

Boiling is the vigorous bubbling that occurs within the body of a liquid as it vaporizes internally. A bubble is a quantity of gas or vapour surrounded by liquid. Imagine a pot of water being heated (Figure 2.1.6). Some molecules at the bottom of the pot are receiving so much heat and consequently moving so fast that they bounce around pushing other water molecules away from them. This produces a bubble. The vapour pressure inside the bubble acts to inflate the bubble while the weight of the water and air above the bubble creates an opposing pressure that acts to collapse the bubble. As the bubble rises, the water vapour molecules transfer energy to the water molecules around the bubble. This causes the vapour molecules to lose energy so the bubble shrinks and collapses before it reaches the surface.

Figure 2.1.6 *Vigorously boiling water. The bubbles are rising to the surface without collapsing.*

The entire pot of water is not yet boiling because it has not yet reached the boiling point. This process continues, transferring energy from the bottom of the pot to the top until all of the water molecules are moving as fast as possible without entering the gas phase. Only at this point, when the bubbles rise to the surface of the water without collapsing is the entire pot of water boiling. Just before breaking through the water's surface the bubble is only opposed by the atmospheric pressure above the liquid. One definition of boiling point is the temperature at which the substance's vapour pressure (the pressure inside that bubble) equals the surrounding air pressure. The air pressure above the sample could be lowered by placing the sample in a vacuum chamber or by taking it to a higher elevation. This would lower the substance's boiling point because the bubbles would have less opposing pressure.

Boiling point is also defined as a substance's highest possible temperature in the liquid state at any given atmospheric pressure. It therefore represents the highest kinetic energy the substance's particles can possess in the liquid state. As the temperature of the water approaches 100°C, more and more of the molecules have their maximum kinetic energy in the liquid state until at 100°C all the molecules are moving at the same maximum speed in the liquid state.

Boiling point, vapour pressure, and volatility are three closely related properties that are all relevant to boiling. **Volatile** substances are substances that readily evaporate or evaporate at high rates. They have high vapour pressures and low boiling points.

Heat of Fusion (H_f)

The **heat of fusion** is the amount of heat required to melt a specified amount of a substance at its melting point. It represents the difference of potential energy between the solid and liquid states since only the substance's state, not its temperature, is changing. **Potential energy** is stored energy. Objects have stored energy by virtue of their position or shape. The heat of fusion is released when the specified quantity of the substance freezes. Heat of fusion is measured in joules per gram.

Heat of Vaporization (H_v)

The **heat of vaporization** is the amount of heat required to evaporate a specified amount of a substance at its boiling point. It represents the difference of potential energy between the liquid and gas states since only the substance's state, not its temperature, is changing. The heat of vaporization is released when the specified quantity of the substance condenses. The heat of vaporization indicates the strength of the force holding the liquid particles together in the liquid state. Heat of vaporization is measured in units such as joules per gram.

Quick Check

1. What is melting? ____________________
2. What is boiling? ____________________
3. What is the heat of fusion? ____________________

Reading a Heating Curve

As energy is added to a solid, the temperature changes. These changes in temperature can be illustrated in a graph called a heating curve. Figure 2.1.7 illustrates an ideal heating curve for water. Note the first plateau in the graph. As a solid melts slowly in its own liquid, the temperature of the liquid will not rise if the melting converts kinetic energy into potential energy as fast as the heat is being added. As the amount of solid decreases, it becomes less able to remove the heat as fast as it is being added. This usually causes the melting segment on the graph to curve upward on the right, rather than remaining horizontal as shown on the ideal heating curve (Figure 2.1.7). The amount of heat needed to melt the ice is the heat of fusion. Once all the ice has melted the water's temperature will begin to increase.

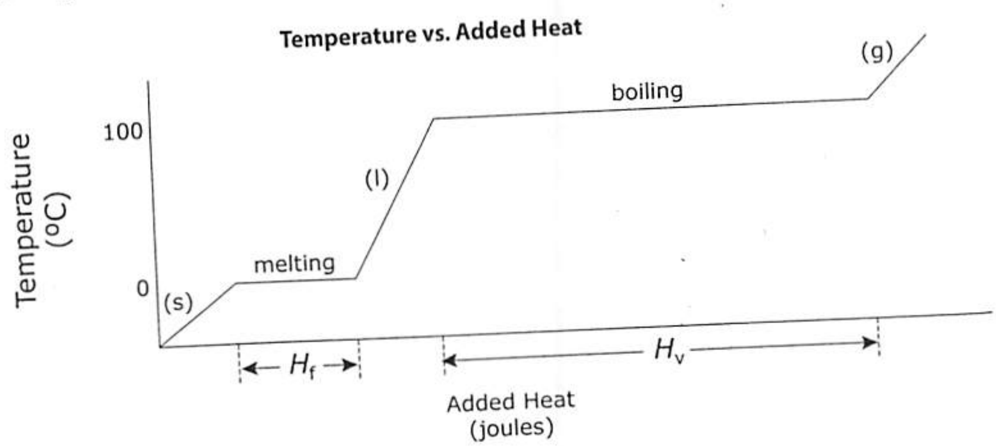


Figure 2.1.7 *Ideal heating curve of water (not to scale)*

Some Chemical Properties of Substances

Reactivity

Reactivity refers to whether a substance reacts or to its reaction rate. Both of these properties are temperature dependent but otherwise depend on different underlying factors. Reaction rates depend on the path from reactants to products, particularly which reactant bonds require breaking. Reaction rates also depend on properties such as reactant concentration. On the other hand, whether or not a reaction will occur depends only on the beginning and end states. Chemical reactions occur because the organization and potential energy of the atoms in the products are favoured over those in the reactants.

Heat of Formation

The **heat of formation** is the heat released when a substance is formed from its elements. The heat of formation is measured in joules per gram.

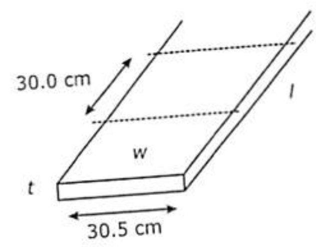
Heat of Combustion

The **heat of combustion** is the heat released when a specified amount of a substance undergoes complete combustion with oxygen. It is usually measured in units such as joules or kilojoules per gram.

Table 2.1.2 *Some Thermal Properties of Selected Substances*

Substance	Melting Point (°C)	Boiling Point (°C)	Heat of Fusion (J/g)	Heat of Vaporization (J/g)	Heat of Combustion (J/g)	Heat of Formation (J/g)
methane	−182.5	−161.6	69	511	54 000	4 679
ammonia	−77.7	−33.3	333	1 374	22 471	2 710
water	0.0	100.0	334	2 259	—	13 400
magnesium	650	1091	349	5 268	12 372	—

2.1 Activity: The Thickness of Aluminum Foil



Not to scale

Question

What is the thickness of a sheet of aluminum foil?

Background

The thickness of a sheet of aluminum foil is an extensive property that is difficult to measure directly with reasonable precision and accuracy. The thickness of the foil can however be derived by dividing its volume by the surface area of one side as proven below:

$$\frac{\text{volume}}{\text{surface area}} = \frac{\cancel{\text{length} \times \text{width}} \times \text{thickness}}{\cancel{\text{length} \times \text{width}}} = \text{thickness}$$

Obviously you can't calculate the volume of the sheet using the formula $V = lwt$ because you don't know the foil's thickness. You will have to calculate its volume by dividing its mass (another extensive property) by its density (an intensive property).

Procedure

1. Mark two points 30 cm apart on one edge of a piece of aluminum foil (see diagram).
2. Repeat step 1 on the parallel edge.
3. Draw a straight line between adjacent points on the opposite edges.
4. Use a razor blade or scissors to carefully cut out your marked section of foil.
5. Scrunch up your piece of foil and weigh it on a milligram scale.

Results and Discussion

Length (cm)	Width (cm)	S. Area (cm^2)	Mass (g)	Density (g/cm^3)	Volume (cm^3)	Thickness (cm)
30.0	30.5			2.702		

1. Calculate the surface area of one side of the foil (length × width). The standard width of a roll of aluminum foil is 30.5 cm, as indicated on the box.

2. Calculate the volume of the piece of foil.

   volume = ________ g Al × $\frac{1\ cm^3\ Al}{2.702\ g\ Al}$ = ________ cm^3

3. Calculate the thickness of the sheet of foil.

   thickness = $\frac{\text{volume}}{\text{surface area}}$ = $\frac{\_\_\_\_\_\ cm^3}{\_\_\_\_\_\ cm^2}$ = ________ cm

4. Aluminum atoms have a diameter of 0.286 nm. If aluminum atoms were stacked linearly, one on top of the other, how many atoms thick would this sheet of Al foil be?

5. This technique is remarkably reliable. Compare your results to those of the other groups.

2.1 Review Questions

1. In each pair of items below, which is a form of matter and which is a property?
   (a) vapour, vapour pressure
   (b) freezing point, solid

2. What are two properties shared by all matter?

3. How was the alchemists' view of matter and its properties different from ours today?

4. Describe three general properties that would be desirable for a material(s) being used for the outer sole of tennis shoes.

5. You sometimes choose one brand over another because it has properties that you prefer. List three properties of paper towels that might influence your choice of which brand to purchase.

6. Whether a property is intensive or extensive often depends on how it is expressed. State whether each of the following physical properties is intensive or extensive.
   (a) temperature
   (b) thermal energy
   (c) thermal expansion (the change in volume in response to a change in temperature)
   (d) coefficient of thermal expansion (the fractional change in volume per degree Celsius change in temperature)
   (e) specific heat capacity (the joules of heat required to raise 1 g of the material by 1°C)
   (f) heat capacity (the joules of heat required to raise the temperature of the object 1°C)

7. State whether each phrase refers to a physical or a chemical property.
   (a) changes of state or form
   (b) relationships or interactions between matter and energy
   (c) only evident through a chemical reaction or a lack thereof
   (d) dependent solely on the relationships between the material's own particles
   (e) relationships or interactions between different forms of matter

8. State whether each of the following properties is physical or chemical.
   (a) heat of vaporization
   (b) heat of formation
   (c) corrosion resistance
   (d) electrical resistance
   (e) flammability (how easily something will burn or ignite)
   (f) speed of sound through the material

9. Composite materials (or just composites) consist of two or more constituent materials that adhere to each other but remain separate and distinct (e.g. the materials could be layered on each other). Why do you think manufacturers sometimes use composite materials in their products?

10. What two properties of particles affect the temperature of the material they compose?

11. Density is mass per unit volume, commonly the amount of matter in one cubic centimetre of the material. What two properties of particles affect the density of the material they compose?

12. Briefly explain what causes materials to expand at the particle level when heated.

13. List the defining physical properties of each phase of matter; solids, liquids, and gases.

14. Does an individual atom or molecule have a melting point? Explain.

15. Describe what is occurring at the molecular level when a material melts.

16. Why doesn't the temperature of an ice water bath (a mixture of ice and water) increase as it absorbs heat from a classroom?

17. Under what condition do all the particles of a liquid have the same kinetic energy?

18. Provide an operational (what to look for) and a conceptual (an explanation) definition of boiling point.

19. (a) Which is greater, a substance's heat of fusion or its heat of vaporization?

(b) Explain in terms of relationships why this would be expected.

20. (a) Which is greater, a substance's heat of vaporization or its heat of combustion?

(b) Explain in terms of relationships why this would be expected.

21. Sensorial properties describe our senses of a material. Rather than being the properties of something, they are actually the properties of our interaction with that thing. Are sensorial properties such as taste and odour physical properties or are they chemical properties?

22. Label and describe briefly a physical change and a chemical change on the drawing of the lit candle.

23. Students change classes at designated times throughout the day in most secondary schools. How is this event like a chemical change or reaction?