6.1 Warmth and Coldness

When you dip your toe into a swimming pool to test the warmth of the water before jumping in, you are using your sense of touch to determine how hot or cold a substance is. While touch helps us sense large differences in warmth or coldness, small differences can go unnoticed. For example, you might be able to feel the difference in warmth between an egg in the refrigerator and an egg frying in a skillet, but you might not notice any difference between an egg in the refrigerator and the same egg left on a kitchen counter for a minute or two. What is the difference between a cold egg and a hot egg? Why is a cold egg cold and a hot egg hot? How can we accurately measure the warmth and coldness of objects?

Warmth and Coldness Are Produced by the Vibrations of Atoms and Molecules

During the eighteenth century, scientists thought that warmth and coldness were produced by a massless fluid called "caloric." Scientists believed that the amount of this fluid in the universe was constant and that it flowed naturally from warmer objects to colder objects. In 1798, English scientist Benjamin Thompson (known as Count Rumford) published his investigations showing that caloric did not exist. Count Rumford noticed that when holes were drilled into large, solid iron cylinders used to build cannons, the drilling apparatus and the iron cylinders would become very hot even though both had been lukewarm at the beginning of the process. This seemed to imply that caloric was not flowing from a warmer object to a colder one, but was being created by rubbing two objects together. You might experience the same effect by rubbing the palms of your hands together very rapidly (**Figure 1**).

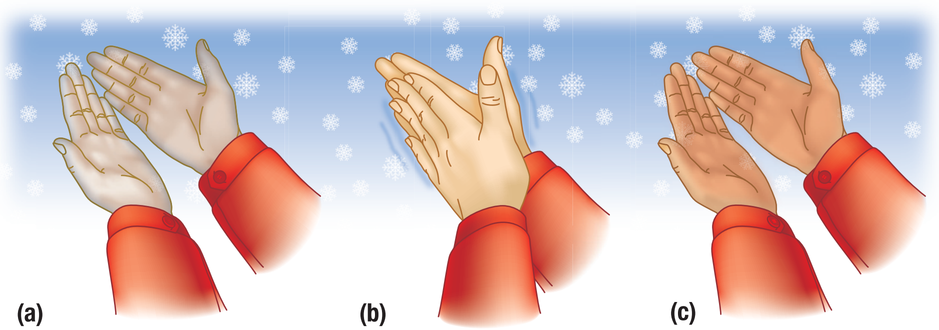

Figure 1 (a) Your bare hands become cold outside in the winter. (b) When you rub your hands together, they warm up. (c) What causes your hands to become warm?

Up until this time, scientists thought that materials could become hot only if they are in contact with even hotter materials that could transfer caloric to them. Count Rumford's investigations caused scientists to lose confidence in the caloric theory's explanation of why objects are hot or cold. Instead, scientists began to explain warmth and coldness using a theory called the kinetic molecular theory.

kinetic molecular theory the theory that describes the motion of molecules or atoms in a substance in terms of kinetic energy

The **kinetic molecular theory** is based on the idea that matter is composed of particles (atoms and molecules) that attract each other and have kinetic energy. It is the kinetic energy that causes particles to be in a state of constant motion. In a solid, such as ice, the particles are held in fixed positions by the forces of attraction between them and vibrate because of the kinetic energy they possess (**Figure 2(a)**). If a solid is warmed up, the particles remain in fixed positions but begin to vibrate more rapidly. According to the kinetic molecular theory, an increase in the motion of the particles of a substance makes the substance feel warmer; a decrease in the motion makes the substance feel colder.

In a liquid, such as liquid water, the particles have more kinetic energy than those of a solid. This causes the particles to vibrate even more rapidly and also to move from place to place, although not very far from each other. This additional motion gives liquids the ability to flow (**Figure 2(b)**).

The particles of a gas have more kinetic energy than those of liquids or solids. This causes them to vibrate and move from place to place much farther and more rapidly than the particles of liquids or solids (**Figure 2(c)**).

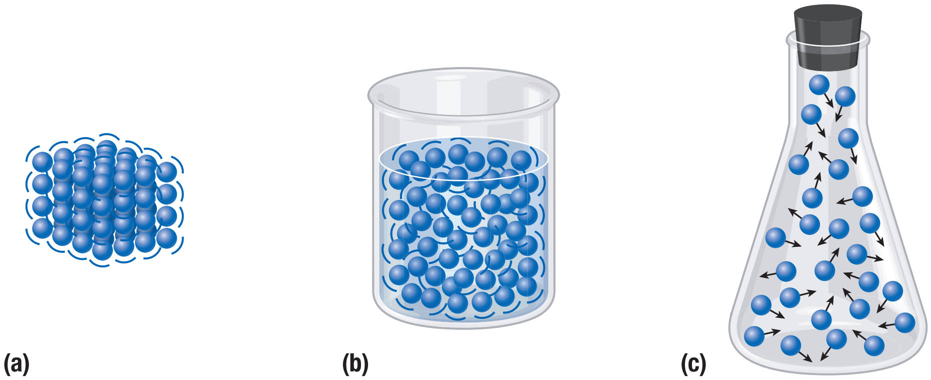

Figure 2 (a) Particles in solids are very close together and can only move back and forth within a very limited range. (b) Particles in liquids are very close together but are able to move and slide past one another. (c) Particles in gases can move freely past each other.

Thermal Energy

Particles of matter possess many forms of kinetic energy and potential energy. Much of the kinetic energy is associated with the motion of the atoms or molecules, while much of the potential energy is associated with the force of attraction between these particles. The total amount of kinetic and potential energy possessed by the particles of a substance is called **thermal energy**.

thermal energy the total quantity of kinetic and potential energy possessed by the atoms or molecules of a substance

In general, the amount of thermal energy within an object determines how fast its particles move (vibrate) and, therefore, how hot or cold the object is. When an object or substance absorbs thermal energy, it warms up; when it releases thermal energy, it cools down. Thermal energy can be transferred from a warmer object to a colder object, but not from a colder object to a warmer object. The thermal energy of an object can also be transformed into other forms of energy. Thermal energy, like all other types of energy, is measured using the SI unit of joules.

Temperature and Thermometers

If thermal energy is responsible for the warmth or coldness of an object, how can we measure the amount of thermal energy that an object has? Unfortunately, there is no way to measure the total amount of thermal energy in an object, because it is impossible to measure the kinetic energy and potential energy of *every* particle within the object. However, there is a way to measure the average kinetic energy of the particles, which gives us an indication of how hot or cold an object is. **Temperature** is a measure of the average kinetic energy of the particles in a substance.

temperature a measure of the average kinetic energy of the particles in a substance

Notice that temperature is a measure of *average* kinetic energy, not total kinetic energy. The reason is that the particles of an object at a particular temperature have different amounts of kinetic energy; some particles move faster than others. However, the majority of the particles of a warmer object move faster than the majority of the particles of a colder object. So, the temperature of a warmer object is higher than the temperature of a colder object.

Temperature is often measured using a mercury or an alcohol thermometer. These thermometers have a narrow, sealed glass tube containing liquid mercury or coloured alcohol. When a thermometer is placed within a liquid or gas, the particles of the substance bump into the glass of the thermometer (**Figure 3(a)**). As the temperature of the substance increases, these collisions cause the particles of the glass to vibrate with greater intensity. In turn, the fast-moving particles of the glass tube collide with the slower-moving particles of the mercury or alcohol inside the tube, making these particles move faster as well. The faster-moving particles of mercury or alcohol begin to spread out and take up more space. This causes the liquid in the thermometer to move higher up the tube and give a higher temperature reading (**Figure 3(b)**).

If a thermometer is placed in a substance that is colder than the thermometer, the glass particles of the thermometer collide with the slower-moving particles of the substance, transferring energy to them. This causes the glass particles to slow down. In turn, the particles of the mercury or alcohol in the thermometer collide with the slower-moving particles of the glass, transferring energy to them. This causes the mercury or alcohol particles of the thermometer to slow down, take up less space, move lower in the tube, and give a lower temperature reading.

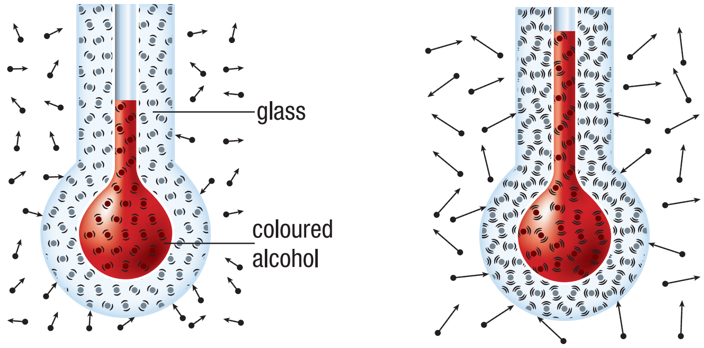

Figure 3 (a) The particles of a thermometer in a colder environment move with less vigour and occupy a smaller volume than in (b) a warmer environment.

Temperature Scales

Celsius scale the temperature scale based on the boiling point and freezing point of water

Fahrenheit scale the temperature scale based on the boiling point and freezing point of brine

Kelvin scale the temperature scale developed using absolute zero as the point at which there is virtually no motion in the particles of a substance

The units for temperature depend on the type of scale that is used. For example, the Celsius scale is used by weather forecasters to report air and water temperatures and by nurses when they measure the temperature of our bodies when we are sick. The **Celsius scale** is named after Anders Celsius, a Swedish scientist, who based the scale on the temperature at which water boils and freezes. On the Celsius scale, pure water freezes at 0 °C and boils at 100 °C.

Another temperature scale is the Fahrenheit scale. The **Fahrenheit scale** was invented by Daniel Gabriel Fahrenheit and is based on the temperature at which a brine (salt-water) solution freezes and boils. On the Fahrenheit scale, pure water freezes at 32 °F and boils at 212 °F. Although the Fahrenheit scale is still used in the United States, it is not an SI unit.

Scientists often use the **Kelvin scale**, instead of the Celsius or Fahrenheit scale, to measure temperature. The Kelvin scale was created by Irish scientist William Thomson, also known as Lord Kelvin. The Kelvin scale is not based on the freezing and boiling points of water or brine, but on the total amount of thermal energy that substances possess. The lowest point on the Kelvin scale, called absolute zero, is the temperature at which the particles of a substance have slowed down so much that they hardly move at all. At this point, the kinetic energy of the particles approaches zero. Absolute zero, or 0 K, occurs at approximately −273 °C. The SI unit for temperature is the kelvin (K). To convert from the Kelvin scale to the Celsius scale (and vice versa), you can use the following equations, where T_C is the temperature in degrees Celsius and T_K is the temperature in kelvins:

$$T_C = T_K - 273$$

$$T_K = T_C + 273$$

In the following Tutorial, you will use these equations to convert a given temperature from one scale to the other.

Tutorial 1 Converting between Celsius and Kelvin Temperature Scales

In the following Sample Problems, you will convert degrees Celsius to kelvins, and kelvins to degrees Celsius.

Sample Problem 1

Ethyl alcohol boils at a temperature of 78.3 °C. What is this temperature in kelvins?

Given: $T_C = 78.3\ °C$

Required: T_K

Analysis: $T_K = T_C + 273$

Solution: $T_K = T_C + 273$

$= 78.3 + 273$

$T_K = 351\ K$

Statement: Ethyl alcohol boils at 351 K.

Sample Problem 2

Ethyl alcohol freezes at 159 K. What is this temperature in degrees Celsius?

Given: $T_K = 159\ K$

Required: T_C

Analysis: $T_C = T_K - 273$

Solution: $T_C = T_K - 273$

$= 159 - 273$

$T_C = -114\ °C$

Statement: Ethyl alcohol freezes at −114 °C.

Practice

1. Convert each temperature to kelvins. T/I
   (a) 32 °C [ans: 305 K]
   (b) −10 °C [ans: 263 K]
   (c) 95 °C [ans: 368 K]
2. Convert each temperature to degrees Celsius. T/I
   (a) 200 K [ans: −73 °C]
   (b) 373 K [ans: 100 °C]
   (c) 298 K [ans: 25 °C]

Mini Investigation

Film Canister Thermometer

Skills: Observing, Analyzing, Evaluating

SKILLS HANDBOOK A2.1

In this activity, you will construct a film canister thermometer and compare its accuracy with that of a regular thermometer.

Equipment and Materials: thermometer; film canister with hole in its lid; beaker; plastic drinking straw; fine-tipped marker; ice water; food colouring; white glue

1. Push the straw through the hole in the lid of the film canister. The straw should be positioned so that it is just above the bottom of the canister, but not touching the bottom. Apply glue around the straw where it meets the canister lid to create a seal.
2. Use the regular thermometer to measure the temperature of the ice water.
3. Fill the canister half-full with ice water and add a drop or two of food colouring. Put the lid on the canister.
4. Use the marker to mark the level of the water on the straw. Label this with the temperature you measured in Step 2.
5. Allow the canister thermometer to warm up to room temperature overnight. Observe the canister thermometer the next day. As the canister thermometer warms up, the level of the coloured water in the straw will rise.
6. Find the room temperature using the regular thermometer. Mark this temperature on the straw.
7. Measure the distance between the two marks. Determine the number of degrees Celsius between the marks.
8. Create a scale that allows you to place 1 °C increments on the straw of the canister thermometer.
9. Put some cold tap water in a beaker. Use the canister thermometer to measure the temperature of the cold water. Check the reading by comparing it to the temperature you get using the regular thermometer.

A. Explain how the canister thermometer works. K/U T/I
B. Discuss the accuracy of this type of thermometer. K/U
C. Suggest some ways in which the design of the thermometer may be improved. T/I
D. How practical is the canister thermometer when measuring the temperature of a liquid? A

melting point the temperature at which a solid changes into a liquid; equal to the freezing point for a given substance

freezing point the temperature at which a liquid changes into a solid; equal to the melting point for a given substance

boiling point the temperature at which a liquid changes into a gas; equal to the condensation point for a given substance

condensation point the temperature at which a gas changes into a liquid; equal to the boiling point for a given substance

Thermal Energy, Temperature, and Physical State

Substances increase in temperature (warm up) when they absorb thermal energy and decrease in temperature (cool down) when they release thermal energy. When thermal energy is absorbed by a solid substance, the solid eventually melts into a liquid. The temperature at which a solid melts into a liquid is called the **melting point**. Conversely, when a liquid is cooled down, it eventually freezes. The **freezing point** is the temperature at which the liquid begins to freeze into a solid. For most substances, the melting point is the same as the freezing point.

If a liquid absorbs enough thermal energy, it eventually becomes a gas. The temperature at which a liquid changes into a gas is called the **boiling point**. Conversely, when a gas releases thermal energy, it cools down and eventually condenses into a liquid. The temperature at which a gas changes into a liquid is called the **condensation point**. For most substances, the boiling point is the same as the condensation point.

6.1 Summary

- Thermal energy is the total potential and the total kinetic energy possessed by the particles of a substance.
- Temperature is a measure of the average kinetic energy of the particles in a substance.
- The kinetic molecular theory states that as particles of matter gain kinetic energy, they move faster and the temperature of the substance increases. Similarly, as particles of matter lose kinetic energy, they move more slowly and the temperature of the substance decreases.
- Temperature can be measured using the Celsius scale, Fahrenheit scale, or Kelvin scale. Scientists typically use the Kelvin scale because kelvins are SI units.
- The equations $T_C = T_K - 273$ and $T_K = T_C + 273$ can be used to convert temperatures from one scale to the other.

6.1 Questions

1. Differentiate between temperature and thermal energy. K/U
2. Describe how the kinetic molecular theory explains the changes of state in substances. K/U
3. How does a mercury or an alcohol thermometer work? K/U
4. Copy **Table 1** in your notebook and fill in the missing values. K/U T/I

Table 1 Boiling Points of Various Substances

Substance	Boiling point (°C)	Boiling point (K)
sodium	882.9	
helium		4.22
copper	2567	
mercury		630

5. Research to find out more about how the caloric theory was disproved. T/I
6. Why does the volume of alcohol in a thermometer decrease when the thermometer is moved from a warm environment into a colder environment? K/U
7. What is the relationship between the freezing point and the melting point of most substances? K/U

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