6.4 States of Matter and Changes of State

Figure 1 (a) The blue sign shows how far the Athabasca glacier has retreated since 1925. (b) Glacier ice melting into liquid water

Glaciers are huge masses of ice and snow that once covered most of Earth's surface. Many of the world's glaciers are retreating at an alarming rate. This means that they are getting smaller. The Athabasca glacier near Banff, Alberta, has retreated over 1.5 km in the last 120 years (**Figure 1(a)**). Scientists know that global warming is responsible for the retreat of the glaciers. Warm temperatures cause the ice and snow of a glacier to melt into liquid water (**Figure 1(b)**). The liquid water flows away from the glacier, forming rivers, lakes, and streams that make their way to the oceans. If the melted ice is not replaced by new ice, the glacier will retreat.

States of Matter

Water, and all other forms of matter, can exist in three different physical states, or phases: solid, liquid, and gas. The kinetic molecular theory described in Section 6.1 explains the differences between these physical states. In a solid, strong forces of attraction (bonds) hold the particles in fixed positions. The particles of a solid vibrate, but they cannot easily slide past each other or move from place to place. This gives solids their rigidity and allows them to maintain their shape. The particles of a liquid are also attracted to each other. However, in liquids, the particles have more kinetic energy than the particles of a solid. This causes the liquid's particles to vibrate more than the particles of a solid, and also to slide past each other and move from place to place. This gives liquids the ability to flow and pour. Like solids and liquids, the particles of a gas are attracted to each other. However, gas particles have much more kinetic energy than the particles of solids and liquids. The particles of a gas vibrate more vigorously than the particles of solids and liquids, and they move large distances past each other. This gives gases their ability to flow and to fill expandable containers like balloons and tires with great pressure.

Changes of State

When solids, liquids, or gases absorb or release enough thermal energy, they may change state (**Figure 2**). For example, a solid can change into a liquid and a liquid can change into a gas. When a substance absorbs thermal energy, the particles of the substance begin to move faster and farther apart. Note that the thermal energy is not really "absorbed"; it is transformed into kinetic energy and potential energy of the substance's particles. Remember that energy is always conserved. It can be transformed from one form into another, but it cannot be destroyed.

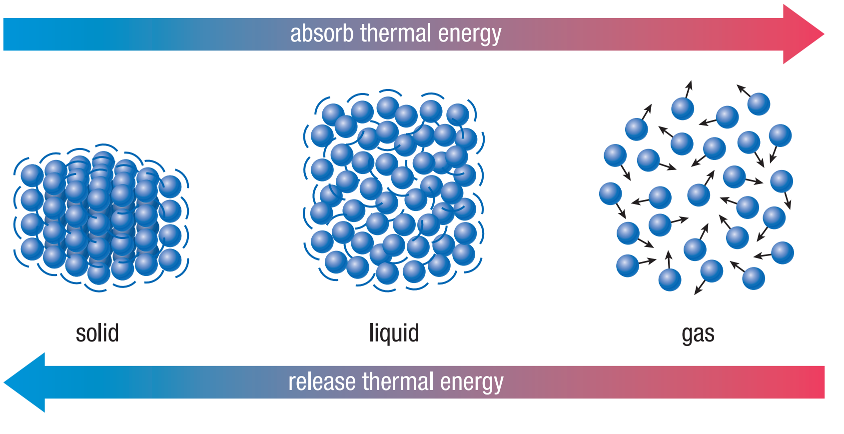

Figure 2 A change of state requires a change in the thermal energy of the substance.

Let us consider what happens to a sample of ice initially at −10 °C when it is continuously heated. When the ice is placed on the hot plate, its initial temperature is −10 °C (**Figure 3(a)**). As the ice absorbs thermal energy, its particles begin to vibrate more vigorously. This warms up the ice and increases its temperature. As the particles absorb more thermal energy, the forces of attraction are not strong enough to hold the particles in fixed positions. Eventually, the solid reaches its melting point, where the particles begin to slide past each other and move from place to place. At this point, the solid begins to change into a liquid (**Figure 3(b)**). The melting point of water is 0 °C. This change of state is called melting, or **fusion**. Eventually, all of the ice becomes liquid water (**Figure 3(c)**). Notice that thermal energy continues to be absorbed during the melting process, but the temperature does not change—it remains at 0 °C until the last ice crystal has melted into liquid water.

fusion the process by which a solid changes to a liquid

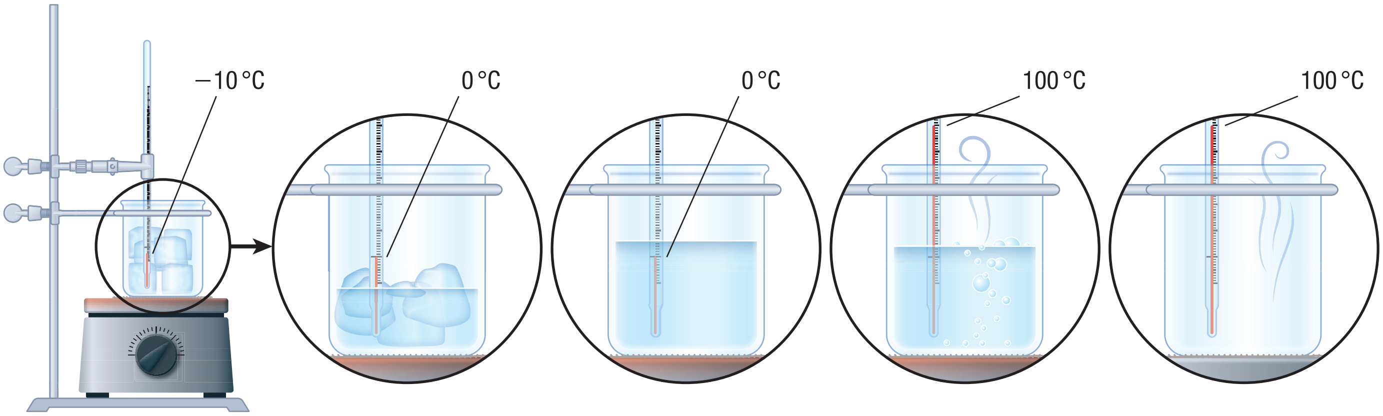

Figure 3 (a) Ice warms up. (b) As the ice reaches its melting point of 0 °C, it begins to change into a liquid because of the absorption of thermal energy. (c) As the ice–liquid water mixture is continuously heated, it continues to absorb thermal energy but stays at a temperature of 0 °C until the ice has completely melted. (d) The liquid water continues to absorb thermal energy until its temperature reaches its boiling point of 100 °C. At this point, enough thermal energy has been absorbed for it to begin to change into a gas, in this case water vapour. (e) The temperature remains at 100 °C until all of the liquid has changed to water vapour.

As the liquid water continues to absorb thermal energy, its particles move faster and farther apart. This warms up the liquid and increases its temperature. As the speed of the particles increases, the forces of attraction become weaker, and it becomes more difficult for the particles to stay together. Eventually, the liquid reaches its boiling point, at which the particles have enough kinetic energy to completely break away from each other. At the boiling point, the liquid water changes into a gas called water vapour (**Figure 3(d)**). The boiling point of water is 100 °C. This change of state is called evaporation or vaporization. Eventually, all of the liquid evaporates into a gas (**Figure 3(e)**). Notice that thermal energy continues to be absorbed during the boiling process, but the temperature does not change—it remains at 100 °C until the last drop of water has changed into water vapour. Changes of state occur whenever any material is heated from a solid to a liquid to a gas. The only difference is that every material has a different melting point and a different boiling point.

Removal of thermal energy reverses this process. In this case, a gas cools down into a liquid and a liquid cools down into a solid. The change of a gas into a liquid is called condensation, and the change of a liquid into a solid is called freezing. In some cases, it is possible for a substance to go directly from a solid to a gas, or vice versa, without ever becoming a liquid. This special change of state is called sublimation. An example of sublimation occurs when ice cubes are kept in a freezer for a long period of time. The ice cubes become smaller and smaller as they sublimate into water vapour.

Heating and Cooling Graphs

heating graph a graph that shows the temperature changes that occur while thermal energy is absorbed by a substance

cooling graph a graph that shows the temperature changes that occur while thermal energy is being removed from a substance

The changes in temperature that occur when a substance absorbs thermal energy can be shown in a graph called a **heating graph.** Similarly, the changes in temperature that occur when a substance releases thermal energy can be shown in a graph called a **cooling graph**. In both graphs, the vertical axis (y-axis) represents temperature and the horizontal axis (x-axis) represents the amount of thermal energy absorbed or released. **Figure 4(a)** is the heating graph for water, and **Figure 4(b)** is the cooling graph for water. An artist's illustration of the state of the water particles is shown above each graph.

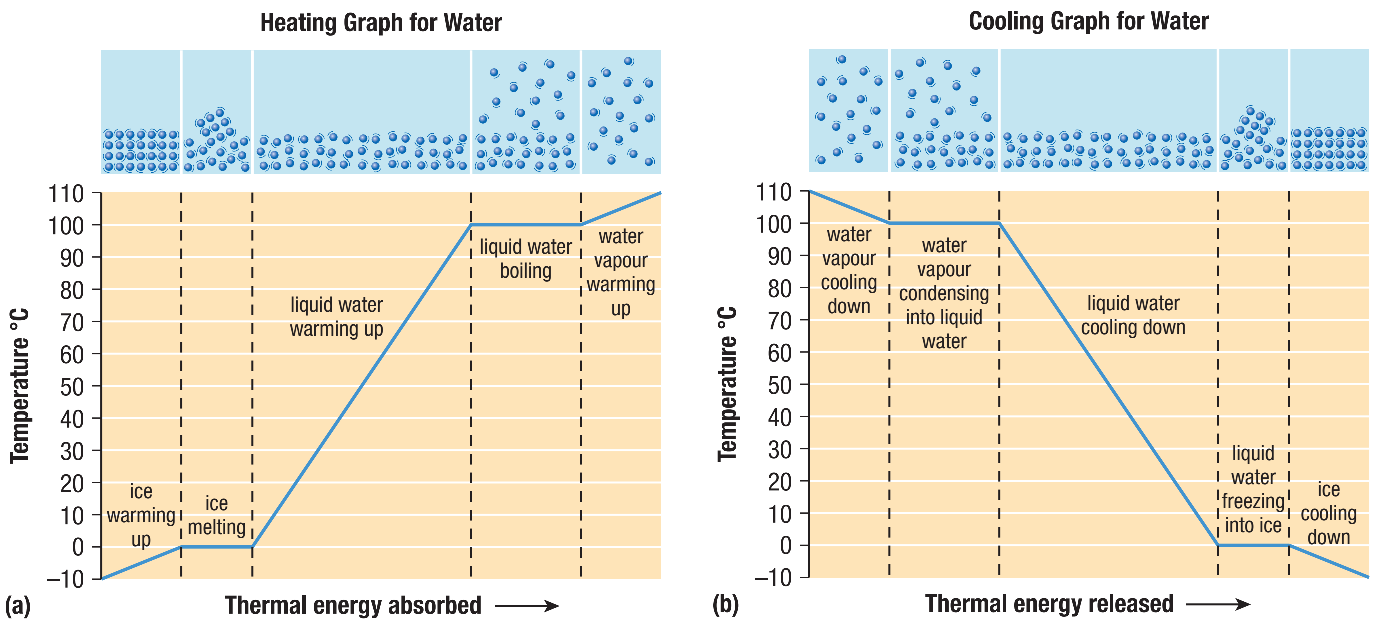

Figure 4 (a) A heating graph and (b) a cooling graph for water. The angled parts on each graph indicate a change in temperature and occur when only one state is present. The flat parts on each graph occur when more than one state is present. The flat parts indicate a constant temperature because one state is changing into another.

Notice the following key aspects of each graph:

- On the heating graph, thermal energy is being absorbed by the water molecules throughout the heating process. On the cooling graph, thermal energy is being released by the water molecules throughout the cooling process.
- Temperature changes occur only when one state is present. These changes are represented by the angled parts of each graph.
- The temperature remains constant during a change of state because thermal energy is being used to change the potential energy of the substance's particles, not their kinetic energy. On the heating graph, this occurs when a solid is changing into a liquid and when a liquid is changing into a gas. On the cooling graph, this occurs when a gas is changing into a liquid and when a liquid is changing into a solid. This is represented by the flat parts of both graphs.
- The heating graph shows a distinct melting point and boiling point. The cooling graph shows a distinct condensation point and freezing point. The melting and freezing points are both 0 °C, and the boiling and condensation points are both 100 °C. In general, melting and freezing occur at the same temperature, and boiling and condensation occur at the same temperature.

You may believe that the temperature of a substance should change while it is absorbing or releasing thermal energy because thermal energy affects the kinetic energy of particles. But why does the temperature not change during melting, freezing, boiling, or condensation?

Investigation 6.4.1

Heating Graph of Water (p. 305)
In this activity, you will observe the temperature change as ice changes into water and create your own heating graph of water.

During melting and boiling, thermal energy must be absorbed by the particles of a substance. This absorbed energy is needed to break the bonds that hold the particles together. However, during condensation and freezing, thermal energy must be released by the particles of a substance. The released energy now allows the particles to move closer together and become more organized. In each of these situations, the change in thermal energy of the substance results in a change in potential energy of the particles. In other words, when a substance melts, boils, condenses, or freezes, the absorbed or released thermal energy is being transformed into potential energy, rather than kinetic energy. Since the kinetic energy of the particles does not change, the temperature of the substance remains constant during a change of state.

Latent Heat

As you have learned, when a substance absorbs or releases thermal energy during a change of state, its temperature remains constant. This absorbed or released thermal energy during a change of state is called the **latent heat (*Q*)** of the substance. The word "latent" means "hidden" because there is no measurable change in temperature. This thermal energy remains "hidden" until the opposite change of state occurs. For example, the thermal energy absorbed when ice melts into liquid water remains in the liquid water until it is released when the liquid water freezes back into ice. Latent heat is measured in joules. Every substance has a latent heat of fusion and a latent heat of vaporization. The **latent heat of fusion** is the amount of thermal energy absorbed when a substance melts or released when it freezes. Note that these energy values are the same for a particular substance because the amount of energy absorbed when a solid melts into a liquid is the same as the amount of energy released when that liquid freezes back into a solid. We use the term "latent heat of fusion" for both values.

The **latent heat of vaporization** is the amount of thermal energy absorbed when a substance evaporates or released when it condenses. As with latent heat of fusion, the energy values required to cause a substance to evaporate or condense are the same, and we use the term "latent heat of vaporization" for both values.

The **specific latent heat (*L*)** of a substance is the amount of thermal energy required for 1 kg of a substance to change from one state into another. Every substance has a different specific latent heat because every substance is composed of different particles (atoms or molecules). The **specific latent heat of fusion (L_f)** is the thermal energy required for 1 kg of a substance to melt or freeze (**Table 1**). The **specific latent heat of vaporization (L_v)** is the thermal energy required for 1 kg of a substance to boil or condense (Table 1). The SI unit for specific latent heats is joules per kilogram (J/kg).

latent heat (*Q*) the total thermal energy absorbed or released when a substance changes state; measured in joules

latent heat of fusion the amount of thermal energy required to change a solid into a liquid or a liquid into a solid

latent heat of vaporization the amount of thermal energy required to change a liquid into a gas or a gas into a liquid

specific latent heat (*L*) the amount of thermal energy required for 1 kg of a substance to change from one state into another; measured in joules per kilogram (J/kg)

specific latent heat of fusion (L_f) the amount of thermal energy required to melt or freeze 1 kg of a substance; measured in joules per kilogram (J/kg)

specific latent heat of vaporization (L_v) the amount of thermal energy required to evaporate or condense 1 kg of a substance; measured in joules per kilogram (J/kg)

Table 1 Specific Latent Heats for Various Substances

Substance	Specific latent heat of fusion (L_f) (J/kg)	Melting point (°C)	Specific latent heat of vaporization (L_v) (J/kg)	Boiling point (°C)
aluminum	6.6×10^5	2519	4.0×10^5	10 900
ethyl alcohol	1.1×10^5	−114	8.6×10^5	78.3
carbon dioxide	1.8×10^5	−78	5.7×10^5	−57
gold	1.1×10^6	1064	6.4×10^4	2 856
lead	2.5×10^4	327.5	8.7×10^5	1 750
water	3.4×10^5	0	2.3×10^6	100

LEARNING TIP

Remember Units
As with all questions in physics, make sure the units in your calculations of latent heat match. Mass must be expressed in kilograms, and latent heat is expressed in joules since the units for specific latent heat are joules per kilogram.

Investigation 6.4.2

Specific Latent Heat of Fusion for Ice (p. 306)
In this investigation, you will use the equations $Q = mc\Delta T$ and $Q = mL_f$ to determine the latent heat of fusion for melting ice.

To calculate the latent heat (Q) involved during a change of state, you can use the equations

$Q = mL_f$ (for substances that are melting or freezing)
$Q = mL_v$ (for substances that are boiling or condensing)

where m is the mass of the substance, L_f is the specific latent heat of fusion, and L_v is the specific latent heat of vaporization.

In the following Tutorial, you will use the specific latent heat of fusion (L_f) and specific latent heat of vaporization (L_v) to calculate the latent heat (Q), or total amount of thermal energy absorbed or released when a substance changes state. In some of the Sample Problems, you will also determine the amount of thermal energy absorbed or released when a substance warms up or cools down but does not change state. In those cases, you will use the quantity of heat equation ($Q = mc\Delta T$) that you learned about in Section 6.3. Note that Q represents both latent heat and quantity of heat. The reason is that both are measures of the amount of thermal energy absorbed or released. The only difference is that latent heat (Q) relates to a substance changing state (temperature remains constant), whereas the quantity of heat (Q) relates to a substance in a particular state (solid or liquid or gas) warming up or cooling down (temperature changes).

Tutorial 1 Calculating Latent Heat of Fusion or Vaporization

Remember that the latent heat equations $Q = mL_v$ and $Q = mL_f$ are used to calculate the amount of thermal energy required for a change of state to occur, whereas the quantity of heat equation $Q = mc\Delta T$ is used to calculate the amount of thermal energy absorbed or released when a solid, liquid, or gas warms up or cools down.

Sample Problem 1

How much thermal energy is released by 652 g of molten lead when it changes into a solid?

Since lead is changing from a liquid to a solid, a change of state is occurring. So, we should use the latent heat equation $Q = mL_f$ to solve this problem.

Given: $m = 652 \text{ g} = 0.652 \text{ kg}$; $L_f = 2.5 \times 10^4 \text{ J/kg}$ (from Table 1)

Required: Q, latent heat of fusion

Analysis: $Q = mL_f$

Solution: $Q = mL_f$

$$= (0.652 \cancel{\text{kg}})(2.5 \times 10^4 \text{ J/}\cancel{\text{kg}})$$

$$Q = 1.6 \times 10^4 \text{ J}$$

Statement: The 652 g of lead releases 1.6×10^4 J of thermal energy as it solidifies.

Sample Problem 2

Ethyl alcohol is a liquid at room temperature. How much thermal energy is absorbed when 135 g of ethyl alcohol at 21.5 °C is heated until all of it boils and turns into vapour?

This is a two-step calculation because the ethyl alcohol will first warm up from 21.5 °C to its boiling point of 78.3 °C (see Table 1 on p. 291) and then change from a liquid into a gas while its temperature remains at 78.3 °C. So there is a warming-up part and a change of state. We will represent the amount of thermal energy absorbed during the warming-up part with Q_1, and the amount of thermal energy absorbed during the change of state with Q_2.

We will use the quantity of heat equation, $Q_1 = mc\Delta T$, to calculate the amount of thermal energy absorbed during the warming phase. For this calculation, we need to use the specific heat capacity, c, of ethyl alcohol from Table 1 in Section 6.3 on page 281.

Then we will use the latent heat equation, $Q_2 = mL_v$, to calculate the amount of thermal energy absorbed during the change of state. For this calculation, we need to use the specific latent heat of vaporization, L_v, of ethyl alcohol from Table 1 in this section.

The total amount of thermal energy absorbed in the entire process, Q_{total}, is the sum of Q_1 and Q_2.

Given: $m = 135 \text{ g} = 0.135 \text{ kg}$; $c = 2.46 \times 10^3 \text{ J/(kg}\cdot\text{°C)}$; $T_1 = 21.5 \text{ °C}$; $T_2 = 78.3 \text{ °C}$; $L_v = 8.6 \times 10^5 \text{ J/kg}$

Required: Q_{total}, total amount of thermal energy absorbed

Analysis: $Q_1 = mc\Delta T$; $Q_2 = mL_v$; $Q_{total} = Q_1 + Q_2$

Solution:

$$Q_1 = mc\Delta T$$
$$= (0.135 \text{ kg})(2.46 \times 10^3 \text{ J/(kg}\cdot\text{°C)})(78.3 \text{ °C} - 21.5 \text{ °C})$$
$$Q_1 = 1.886 \times 10^4 \text{ J (one extra digit carried)}$$
$$Q_2 = mL_v$$
$$= (0.135 \text{ kg})(8.6 \times 10^5 \text{ J/kg})$$
$$Q_2 = 1.161 \times 10^5 \text{ J (two extra digits carried)}$$
$$Q_{total} = 1.886 \times 10^4 \text{ J} + 1.161 \times 10^5 \text{ J}$$
$$Q_{total} = 1.3 \times 10^5 \text{ J}$$

Statement: Ethyl alcohol absorbs a total of 1.3×10^5 J of energy when a 135 g sample at 21.5 °C is heated until all of it boils and turns into vapour.

Practice

1. How much thermal energy is released when 2.0 L of liquid water freezes? T/I [ans: 6.8×10^5 J]
2. How much thermal energy is absorbed when a 350 g bar of gold melts? T/I [ans: 3.9×10^5 J]
3. How much thermal energy is released when 500 g of steam at 100 °C condenses into liquid water and then cools to 50 °C? T/I [ans: 1.3×10^6 J]

Water: A Special Liquid

Most solids sink in their respective liquids. For example, solid iron sinks in liquid iron. This occurs because the particles of the solid are more closely packed than the particles of the liquid, making the solid denser. However, water is different. Ice floats on water because water is one of the few substances whose solid is less dense than its liquid (**Figure 5**). This is based on the water molecule's chemical structure. Water molecules are V-shaped and have two hydrogen atoms attached to one oxygen atom (**Figure 6**).

Figure 5 Most solids are more dense than their liquids. Ice, however, floats on liquid water.

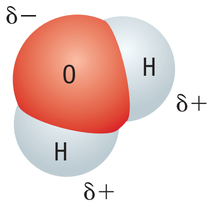

Figure 6 A water molecule has two hydrogen atoms with a slight positive charge and one oxygen atom with a slight negative charge (δ means "partial charge").

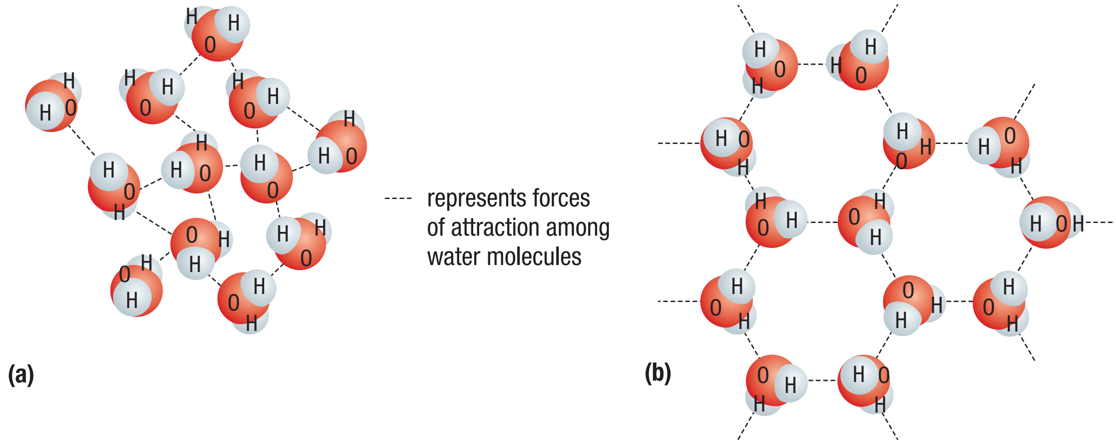

Figure 7 (a) At temperatures above 4 °C, water molecules are relatively disorganized. (b) As the temperature of the water decreases, the molecules move more slowly, forming a more organized structure, so that molecules of ice take up more space than those of liquid water.

The hydrogen atoms in a water molecule have a small positive charge, while the oxygen atom has a small negative charge. The hydrogen atoms of one water molecule are attracted to the oxygen atoms of neighbouring water molecules. This occurs because opposite charges are attracted to one another.

However, at temperatures above 4 °C, molecules of water move too fast for these forces of attraction to pull the molecules together. At these temperatures, water molecules are relatively disorganized (**Figure 7(a)**). As the temperature decreases, the molecules move slowly enough for the forces of attraction to place the molecules into a more organized structure. The more organized molecules of water in ice take up more space than the more disorganized molecules in liquid water, so water expands as it freezes (**Figure 7(b)**).

The expansion of water when it freezes can cause a lot of problems. Pipes in homes or under the street can break under the pressure of the expanding, frozen water. When the water thaws, it flows out of the broken pipes, causing flooding and damage (**Figure 8**).

Figure 8 When pipes freeze and burst, it can be a big mess, both above ground on road surfaces and below ground in water and sewer systems.

6.4 Summary

- The three states of matter are solid, liquid, and gas. When thermal energy is released or absorbed a change of state may happen.
- The change in temperature that occurs as a substance releases or absorbs thermal energy can be shown in a cooling graph or a heating graph.
- The thermal energy that is absorbed or released during a change of state is called the latent heat of the substance. If the substance is melting or freezing, it is called the latent heat of fusion. If the substance is evaporating or condensing, it is called the latent heat of vaporization.
- The specific latent heat of fusion (L_f) is the amount of thermal energy per kilogram needed to melt or freeze a substance. The specific latent heat of vaporization (L_v) is the amount of thermal energy needed per kilogram to evaporate or condense a substance.
- The equation $Q = mL_f$ is used to calculate the latent heat of fusion, and $Q = mL_v$ is used to calculate the latent heat of vaporization.
- Ice is one of the few solids that floats in its liquid; this is due to the shape of its molecules and the forces of attraction between its molecules.

6.4 Questions

1. (a) Describe each part of the graph in **Figure 9** in terms of the states of matter.
   (b) What type of graph is this, a heating graph or a cooling graph? How can you tell? K/U T/I

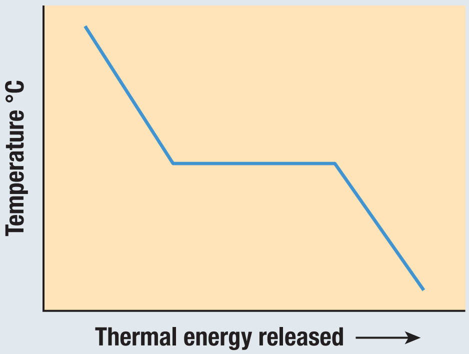

Figure 9

2. (a) Use **Table 2** to graph a heating curve.
   (b) Label the appropriate parts of the graph with the following: solid, liquid, gas, melting, evaporation.
   (c) Determine the melting point and boiling point of the substance. T/I
3. Describe what would happen if you were to heat liquid water to a temperature of 110 °C. K/U
4. Explain the terms "latent heat of fusion" and "latent heat of vaporization." K/U
5. To prevent fruit on trees from freezing and becoming inedible, fruit farmers in Ontario often spray their crops with water if they know the temperatures are going to drop below zero. Use your knowledge of latent heat to explain why this will help prevent the fruit from freezing. K/U A
6. Calculate the latent heat of fusion for 2.40 kg of gold as it changes from a molten liquid into a solid bar. T/I
7. How much thermal energy is needed to change 100 g of ice at −20 °C into steam at 110 °C? T/I
8. While forming a 1.50 kg aluminum statue, a metal smith heats the aluminum to 2700 °C, pours it into a mould, and then cools it to a room temperature of 23.0 °C. Calculate the thermal energy released by the aluminum during the process. T/I
9. What makes water different from most other substances? Include a description of the physical characteristics in your answer. K/U

Table 2 Data Collected during the Heating of a Substance

Time (min)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5
Temperature (°C)	37	43	49	55	55	55	56	64	70	80	86	90	90	90	100