1.4 Temperature in Thermal Systems

Objectives

- Define thermal energy.
- Name the property of a body that determines its temperature.
- Given Celsius or Fahrenheit temperatures and the formula for conversion, find the equivalent temperatures on the alternate scale.
- Explain the difference between heat and thermal energy.
- Explain the relationship between heat transferred to an object and the change in the object's temperature.
- Use specific heat, heat of fusion, and heat of vaporization to solve problems involving heat transfer.

INTERNET *connection*

To find out more about temperature in thermal systems, follow the links at **www.learningincontext.com.**

In Section 1.1 you learned that a force can move an object from one place to another, or change the object's speed if it is already moving. In the next chapter, you will study work. Work is done on an object when a force moves the object through a distance. Therefore, doing work on an object can change its position or its speed.

For example, when you do work in lifting a hammer, the hammer changes its position in the Earth's gravitational field. By being lifted, the hammer gains the ability to do work on a nail beneath the hammer. The property that enables a body to do work is called **energy**. You increase the energy of the hammer when you lift it. You can also increase the energy of a gas by compressing it with a piston in a cylinder. The added energy comes from the work of a force pushing the piston through a distance. You can increase the energy stored in a battery by charging it. The added energy comes from the work of a force that pushes electrons through a distance in an electric field.

When an object gains energy as a result of changing its position, it has the potential for doing work. This energy is called **potential energy**. An object in motion is also capable of doing work. Energy of motion is called **kinetic energy**. When you lift a hammer, you increase its potential energy. As the hammer falls, it converts potential energy into kinetic energy. The kinetic energy of the hammer is converted into work when it hits the nail.

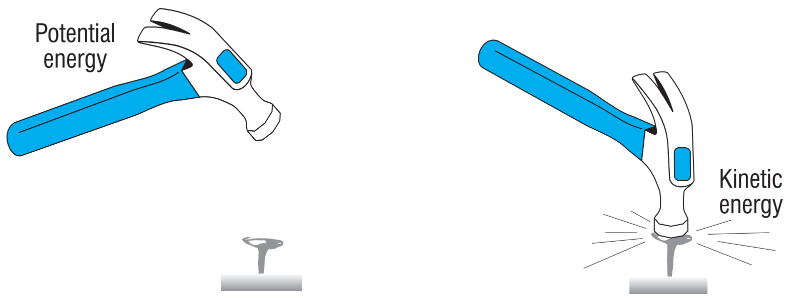


Figure 1.42
Work is done on a hammer to increase its potential energy. Potential energy is converted into kinetic energy.

You will learn more about work and the different forms of energy in later chapters. In this section, we use the concept of kinetic energy to model the energy of motion of atoms and molecules. These particles are always in motion, vibrating back-and-forth randomly. In fact, the rate of this vibration determines whether an object exists in the solid, liquid, gas, or plasma state. The random motion of vibration of an object's atoms and molecules is called *thermal motion*. The total energy of the thermal motion of all the particles that make up an object is called the **thermal energy** of the object.

Temperature

We use thermal energy every day. When you cook a frozen pot pie you increase its thermal energy in an oven. The total kinetic energy of the molecules of a frozen pie is less than the total kinetic energy of the molecules of a cooked pie. If you touch a frozen pot pie with your hand, thermal energy flows from your hand into the pie. The frozen pie is colder than your hand. If you touch a cooked pot pie, thermal energy flows from the pie into your hand. The cooked pie is hotter than your hand. Whenever two bodies are brought together, thermal energy flows from the hotter body to the colder body.

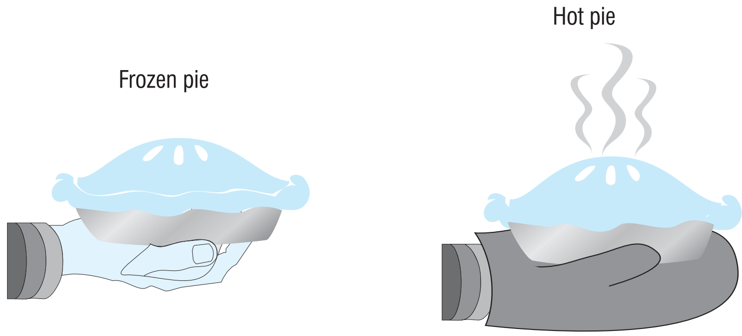


Figure 1.43
Thermal energy always flows from the hot body to the cold body.

The “hotness” of a body is a property called *temperature*. **Temperature** is determined by the average kinetic energy of the random motion of the atoms and molecules in a body. This average energy is not the same as the thermal energy. The thermal energy is the sum of all the particles’ energies, while the average is this sum divided by the number of particles. Notice that the average energy and the temperature of a body do not depend on the total number of particles in the body. The temperature of 1/2, 1/4, or 1/8 of the hot pie is the same as the temperature of the whole pie.

To see why, consider how you would calculate the average age of the students in your class. The sum of all the ages is divided by the number of students to find the average. Notice that the ages of the students are not exactly the same (especially if age is measured in months.) Students have a range of ages from a lowest to a highest value. Now compare the average age of students in your class to the average age of students in 100 eighth-grade science classes. Your average is higher than the eighth-grade average, but the sum of the ages for your class is much lower than the sum of the eighth-grade ages.

In the same way, the thermal energy in a pot of boiling water is lower than the thermal energy of a frozen lake. Water molecules in the boiling water have a range of kinetic energies, and so do the molecules in the lake. The average kinetic energy, or temperature, in the boiling water is higher than the average kinetic energy, or temperature in the lake. But the sum of the energies for the boiling water is much lower than the sum for the lake.

Refer to Appendix F for a career link to this concept.

Measuring Temperature

Thermal energy is measured in joules. Temperature is measured in degrees. Devices for measuring temperature depend on some property of a material that changes when its temperature changes. For example, most materials expand when their temperature increases and shrink when temperature decreases.

A **thermometer** uses expansion and contraction of a liquid, usually colored alcohol or mercury, to measure temperature. The liquid is contained in a glass tube. When the thermometer is placed in contact with an object like hot water, the faster-moving molecules in the water collide with the slower-moving molecules of the glass tube. The collisions transfer energy from the water to the glass. The thermal energy of the glass increases, while the thermal energy of the water decreases. Thermal energy flows between the water and glass, and also between the glass and the liquid inside the glass, until the temperatures are all equal. At this point, the thermometer and water are in **thermal equilibrium**. If you know the temperature of the thermometer, you know the temperature of the water.

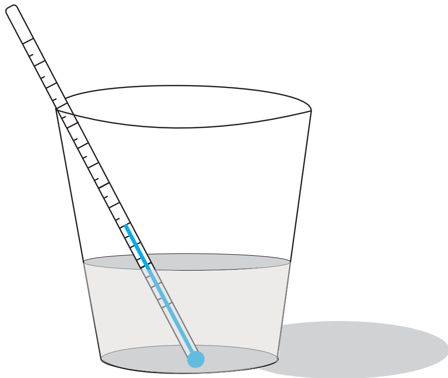


Figure 1.44
When the temperature of the thermometer is the same as the temperature of the water, they are in thermal equilibrium.

As the temperature of the thermometer increases, the liquid inside the glass expands and rises. The temperature of the thermometer is read by comparing the height of the liquid to a scale.

The most commonly used temperature scale was devised in 1741 by the Swedish astronomer and physicist Anders Celsius. The **Celsius** scale is based on the properties of water. Zero degrees Celsius (0°C) is defined as the freezing point of pure water at sea level. One hundred degrees Celsius (100°C) is defined as the boiling point.

In some cases in the United States, the **Fahrenheit** scale is still used. Thirty two degrees Fahrenheit (32°F) is the freezing point of water, and 212°F is the boiling point. The Celsius and Fahrenheit scales are compared in Figure 1.45.

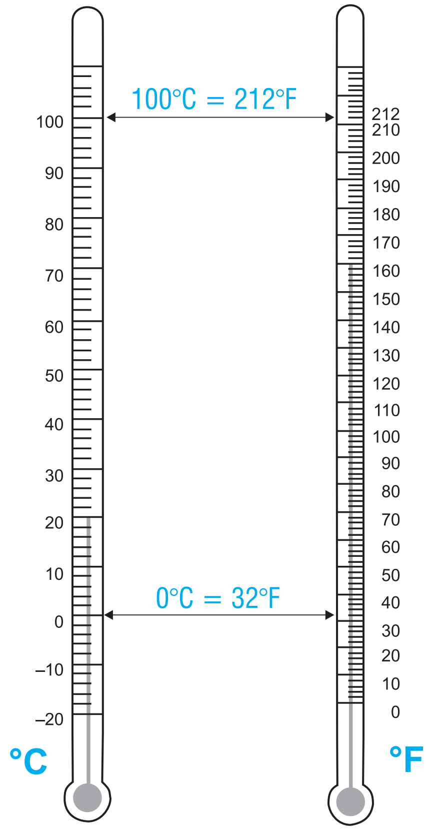


Figure 1.45
The Celsius and Fahrenheit temperature scales

If you know the temperature in degrees Fahrenheit (T_F), you can find the same temperature in degrees Celsius (T_C) by using the following equation:

$$T_C = \frac{5}{9}(T_F - 32)$$

If you know the temperature in degrees Celsius, you can find the same temperature in degrees Fahrenheit by using the following equation:

$$T_F = \frac{9}{5}T_C + 32$$

Example 1.13 Converting °F to °C

A meteorologist forecasts a high temperature of 50°F. What is the predicted high temperature in degrees Celsius?

Solution: Convert 50°F to degrees Celsius.

$$T_C = \frac{5}{9}(T_F - 32)$$

$$= \frac{5}{9}(50 - 32)$$

$$= 10$$

The predicted high temperature of 50°F is the same as 10°C.

Example 1.14 Converting °C to °F

A thermostat is set to keep the temperature of a room at 20°C. What is the thermostat setting in degrees Fahrenheit?

Solution:

$$T_F = \frac{9}{5}T_C + 32$$

$$= \frac{9}{5}(20) + 32$$

$$= 68$$

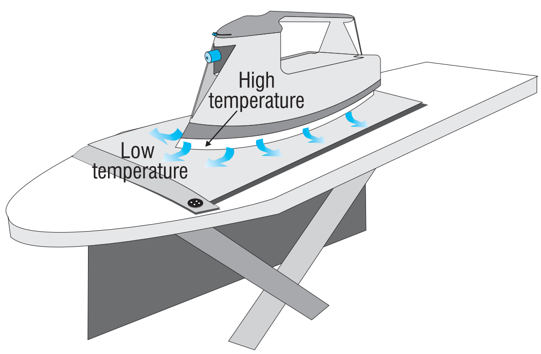
The thermostat setting of 20°C is the same as 68°F.

Heat

When a thermometer is placed in hot water, the temperature of the thermometer increases. This illustrates one way to increase the temperature of any object—place it in contact with a hotter object. Thermal energy flows from the hotter object to the cooler object, as kinetic energy is transferred when particles collide. This process is called **conduction**.

Heat is the energy that flows from one object to another because of a temperature difference. In conduction, heat is the amount of energy that flows from a hotter object to a cooler object after they are placed in contact. Heat never flows from a colder object to a hotter object. Like any measurement of energy or work, heat is measured in joules in the SI system.

Heat is not just another word for thermal energy. A body contains thermal energy, but not heat. Heat is thermal energy in transit. After heat is transferred to a body, it is no longer heat—it becomes thermal energy.



Heat flow depends on a temperature difference, but not necessarily a thermal energy difference. (Remember, temperature is the average kinetic energy of the particles; thermal energy is the total kinetic energy.) For example, when you press a skirt with a hot iron, heat will flow from the iron at a higher temperature to the skirt at a lower temperature. In this case, the thermal energy of the iron is *greater than* the thermal energy of the skirt.

What happens if you take the same hot iron, unplug it, and toss it into a full swimming pool? Heat will still flow from the iron at a higher temperature to the water at a lower temperature. But, in this case, the thermal energy of the iron is *less than* the thermal energy of the water, because there are many more molecules in the swimming pool (with lower average energy) than in the iron (with higher average energy). This is similar to the previous example with average ages.

The amount of heat transferred between two bodies depends on their temperature difference. If there is no temperature difference, there is no heat transfer. As the temperature difference increases, the heat transfer rate increases. Therefore, **temperature difference** is the prime mover in thermal systems. Temperature difference is analogous to the other prime movers:

- In mechanical systems, movement of mass depends on force.
- In fluid systems, movement of fluid depends on pressure difference.
- In electrical systems, movement of charge (current) depends on potential difference (voltage).
- In thermal systems, transfer of heat depends on temperature difference.

In later chapters you will use temperature difference to calculate heat transfer in thermal systems, such as the engine cooling system of an automobile. Actually, the cooling system is a combination of thermal, fluid, and mechanical systems. When the fuel burns, very high levels of heat are transferred to the engine, raising its thermal energy. Heat is transferred from the engine to the coolant (a mixture of water and antifreeze). A pump circulates the coolant through the engine and through the radiator. Heat is transferred from the coolant to the radiator, and then from the radiator to air forced through the radiator by a fan.

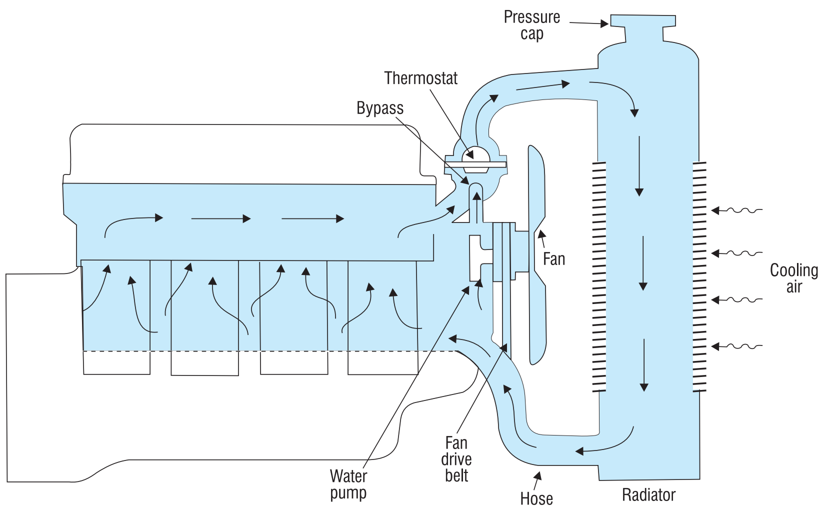


Figure 1.46
The cooling system is a combination of thermal, fluid, and mechanical systems.

Specific Heat

Water is used in the cooling system of an automobile because it has a much higher capacity for storing thermal energy than almost every other substance. A relatively small amount of water can absorb a great deal of heat with a small temperature increase.

In SI, the unit of thermal energy and heat is the joule. Another commonly used unit is the **calorie** (cal). 1 cal = 4.184 J. In some places in the United States, the British thermal unit, or **Btu**, is still used.

> *One calorie is the amount of thermal energy that must be added to water to change the temperature of 1 gram of water by 1 degree Celsius.*
>
> *One Btu is the amount of thermal energy that must be added to water to change the temperature of 1 pound of water by 1 degree Fahrenheit.*

When heat flows into an object, its thermal energy increases. As long as there is no phase change, the object's temperature increases. The amount of increase depends on the mass of the object, and also on the substance of which the object is made. For example, if you heat a pot of water and an equal mass of iron on the same stove top for two minutes, the temperature of the iron will be much higher than the temperature of the water.

The **specific heat** of a substance is the amount of energy that must be added to raise the temperature of a unit mass of the substance one temperature unit. From the definition above, the specific heat of water is $\frac{\text{cal}}{\text{g}\cdot°\text{C}}$. Specific heats of several substances are shown in Table 1.7.

Table 1.7 Specific Heat of Common Substances

Substance	Specific Heat cal/g·°C	Substance	Specific Heat cal/g·°C
Water	1.00	Stone (average)	0.19
Ice	0.49	Iron	0.16
Wood (average)	0.42	Copper	0.093
Air	0.24	Brass	0.091
Aluminum	0.22	Tin	0.055
Glass	0.21	Lead	0.031

The specific heat of a substance is represented by C. (Don't confuse this C with °C for degrees Celsius.) The amount of heat Q transferred to an object of mass m varies with the object's temperature change ΔT as follows:

$$\text{Heat transferred to an object} = \text{object's mass} \times \text{specific heat} \times \text{temperature change}$$

$$Q = mC\Delta T$$

When an object's temperature changes from an initial value of T_i to a final value of T_f, the change is $\Delta T = T_f - T_i$.

Example 1.15 Heat Transfer in Water

A teakettle holds 0.5 liter of water. How much heat is needed to increase the temperature of the water from 20°C to 100°C?

Solution: Water has a density of 1 g/cm³, and 0.5 L = 500 cm³. The mass m of the water is

$$m = \rho V = 1\frac{\text{g}}{\text{cm}^3} \times 500\ \text{cm}^3 = 500\ \text{g}$$

The temperature of the water changes from T_i = 20°C to T_f = 100°C.

$$\Delta T = T_f - T_i = 100°\text{C} - 20°\text{C} = 80°\text{C}$$

$$Q = mC\Delta T$$

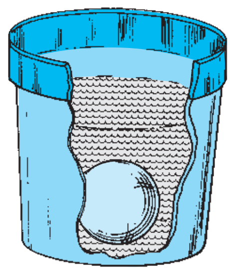
$$= (500\ \text{g})(1\frac{\text{cal}}{\text{g}\cdot°\text{C}})(80°\text{C})$$

$$= 40{,}000\ \text{cal}$$

A heat transfer of 40,000 cal is required to increase the temperature of the water from 20°C to 100°C.

Example 1.16 Heat Transfer to Cool a Ball

A 2.5-kg brass ball at 100°C is placed in an insulated container of water at 10°C. When the ball and water reach thermal equilibrium, their temperature is 30°C.



(a) What amount of heat is transferred between the ball and water?

(b) What is the mass of water in the container?

Solution: (a) Use the fact that $1\frac{\text{cal}}{\text{g}\cdot°\text{C}} = 1\frac{\text{kcal}}{\text{kg}\cdot°\text{C}}$, so from Table 1.7 for brass

$$C = 0.091\frac{\text{kcal}}{\text{kg}\cdot°\text{C}}$$

For the brass ball, $T_i = 100°C$ and $T_f = 30°C$, and

$$\Delta T = T_f - T_i = 30°C - 100°C = -70°C$$

The temperature change is negative because the temperature of the ball decreases.

$$\begin{aligned} Q &= mC\Delta T \\ &= (2.5 \text{ kg})\left(0.091 \frac{\text{kcal}}{\text{kg}\cdot°\text{C}}\right)(-70°\text{C}) \\ &= -15.9 \text{ kcal} \quad \text{or} \quad -15{,}900 \text{ cal} \end{aligned}$$

The heat transfer is negative because the ball loses thermal energy as it cools. 15,900 calories are transferred from the ball to the water.

(b) Since the container is insulated, assume that all the heat lost by the ball is gained by the water. Heat gain is positive. For the water, $\Delta T = 30°C - 10°C = 20°C$. Solve the heat transfer equation for m:

$$\begin{aligned} m &= \frac{Q}{C\Delta T} \\ &= \frac{15{,}900 \text{ cal}}{1 \frac{\text{cal}}{\text{g}\cdot°\text{C}} \cdot 20°\text{C}} \\ &= 795 \text{ g} \end{aligned}$$

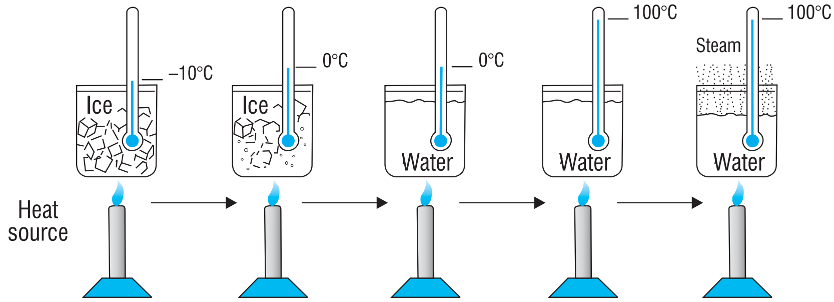
The mass of water in the container is 795 grams or 0.795 kilogram.

Change of State

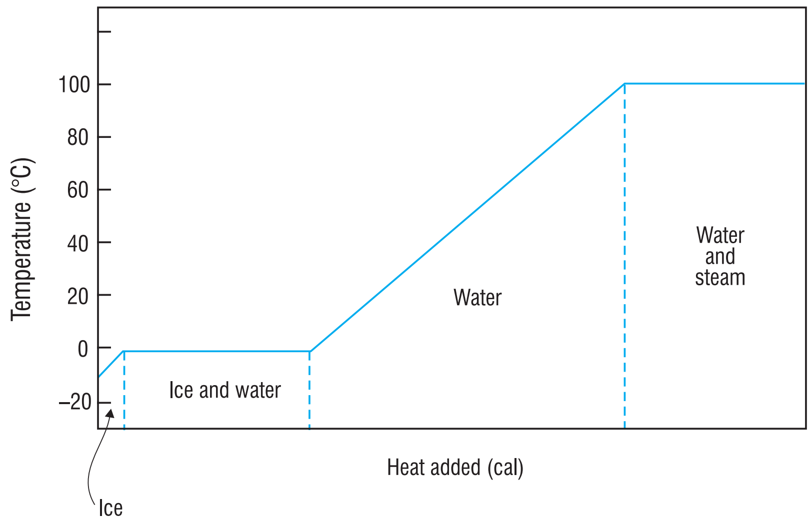
The linear relationship between heat transfer and temperature change of a given amount of a substance, $Q = mC\Delta T$, assumes the substance does not change state. If an object is a solid, like the brass ball in Example 1.16, it stays a solid. If it is a liquid, like the water, it stays a liquid. The relationship does not hold if the object changes state—for example, if it changes from a solid to a liquid, or from a liquid to a gas. The reason is that substances change state at *constant temperature*. When heat is added to a substance and $\Delta T = 0$, the heat transfer equation above does not apply.

Figure 1.47 shows what happens when heat is added to a container of ice, with an initial temperature of –10°C. At first, the temperature of the ice increases linearly as the ice absorbs thermal energy. When the temperature reaches 0°C, the ice begins to change state. This temperature is called the

melting point. The temperature does not change as the ice absorbs thermal energy, melts, and changes from solid to liquid.



(a) Changes of state and temperatures for ice initially at –10°C.



(b) Graph of temperature and heat added for ice initially at –10°C, showing changes of state

Figure 1.47
Q-*T* relationship for ice, water, and steam

When all the water is in the liquid state, it continues to absorb energy, and its temperature increases linearly to 100°C. When the water reaches 100°C, it starts another change of state to gas (steam). This temperature is called the **boiling point**. Again, the temperature is constant; as heat is absorbed, more water is converted to steam.

The amount of energy required to melt one gram of a solid substance is called the **heat of fusion** of the substance. The amount of energy required to vaporize one gram of a liquid is called the **heat of vaporization**. The values of some heats of fusion (H_f) and vaporization (H_v) are listed in Table 1.8.

Table 1.8 Heat of Fusion and Vaporization of Several Substances

Substance	Heat of Fusion H_f (cal/g)	Heat of Vaporization H_v (cal/g)
Water (Ice)	79.8	540
Iron	63.7	1503
Copper	49.0	1212
Silver	25.0	564
Gold	15.3	392
Lead	5.9	207

The amount of heat Q needed to melt a solid of mass m is

$$Q = mH_f \, .$$

The amount of heat Q needed to vaporize a liquid of mass m is

$$Q = mH_v \, .$$

Example 1.17 Melting Ice and Warming Water

A 10-gram ice cube has a temperature of –5°C. How much heat is needed to melt the ice cube and warm the resulting water to room temperature (20°C)?

Solution: Calculate the heat Q_1 needed to increase the temperature of the ice cube to the melting point, from −5°C to 0°C. For ice, $C = 0.49$ cal/g·°C.

$$\begin{aligned} Q_1 &= mC\Delta T \\ &= (10\text{ g})\left(0.49\frac{\text{cal}}{\text{g}\cdot{}^\circ\text{C}}\right)(0^\circ\text{C} - (-5^\circ\text{C})) \\ &= 24.5\text{ cal} \end{aligned}$$

Calculate the heat Q_2 needed to melt the ice:

$$\begin{aligned} Q_2 &= mH_f \\ &= (10\text{ g})\left(79.8\frac{\text{cal}}{\text{g}}\right) \\ &= 798\text{ cal} \end{aligned}$$

Calculate the heat Q_3 needed to raise the temperature of the water from 0°C to 20°C. For water, $C = 1.00$ cal/g·°C.

$$Q_3 = mC\Delta T$$
$$= (10\text{ g})\left(1.00\frac{\text{cal}}{\text{g}\cdot{}^\circ\text{C}}\right)(20^\circ\text{C} - 0^\circ\text{C})$$
$$= 200\text{ cal}$$

The total heat required is the sum:

$$Q = Q_1 + Q_2 + Q_3$$
$$= 24.5\text{ cal} + 798\text{ cal} + 200\text{ cal}$$
$$= 1022.5\text{ cal}$$

Summary

- The thermal energy of a body is the total kinetic energy of motion of all the particles that make up the body.
- The temperature of a body is determined by the average kinetic energy of the particles that make up the body.
- A thermometer measures temperature in degrees Celsius or degrees Fahrenheit.
- Heat is the energy that flows from one body to another because of a temperature difference.
- Whenever two bodies are brought together, heat flows from the body with the higher temperature to the body with the lower temperature.
- The amount of heat transferred to an object varies linearly with the object's temperature change, as long as there is no change of state: $Q = mC\Delta T$.
- If heat is transferred to a substance and it changes state, its temperature does not change.

Exercises

1. The thermal energy in an object is the _________________ of all the kinetic energy associated with the motion of all the atoms and molecules that make up the object.
2. The temperature of an object is determined by the _________________ kinetic energy associated with the motion of all the atoms and molecules that make up the object.

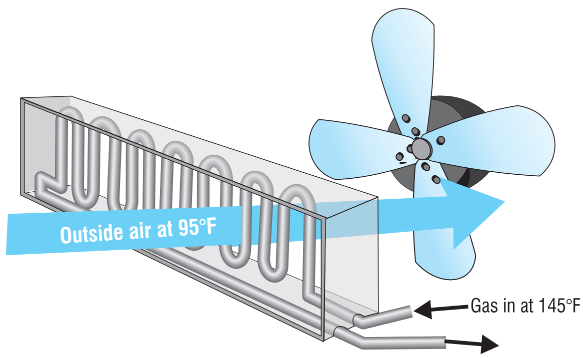
3. A thermometer marked with the Celsius scale is placed in an ice-water mixture and allowed to reach thermal equilibrium with the mixture. The temperature indicated by the thermometer is _______________ .

4. The thermometer from Exercise 3 is placed in a pan of boiling water and allowed to reach thermal equilibrium. The temperature indicated by the thermometer is _______________ .

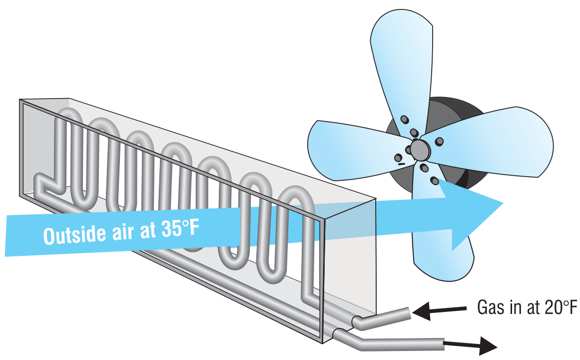
5. A television news report includes an item about a medical care crisis in Sao Paulo, Brazil, due to a period of very hot weather. Sao Paulo has 12 consecutive days with temperatures above 41°C. What is the temperature in degrees Fahrenheit?

6. A severe weather warning for the area near Bettles, Alaska, warns that the low temperature tonight is expected to reach –45°F. What is the temperature on the Celsius scale?

7. A heat pump air-conditioning unit has a heat-exchanger coil on the outside of a house. On a summer day the gas flowing through the coil has a temperature of 145°F when the outside air temperature is 95°F. Will heat flow into or out of the gas in the heat-exchanger coil? Explain your answer.



8. On a winter day the gas flowing through the heat-exchanger coil in Exercise 7 has a temperature of 20°F when the air temperature is 35°F. Will heat flow into or out of the gas in the heat-exchanger coil? Explain your answer.



9. The temperature of an ice cube is 0°C. The temperature of liquid oxygen in a container is –183°C. The ice cube is placed in the liquid oxygen. Will heat flow into or out of the ice cube? Explain your answer.

10. Suppose you could measure very accurately the temperature of water at the top and bottom of a waterfall. Would you expect the temperature to be different? Explain your answer.

11. When wax melts, is heat absorbed or released by the wax?

12. When wax freezes, is heat absorbed or released by the wax?

13. Explain the difference between *thermal energy* and *heat*.

14. Explain the difference between *temperature* and *heat*.

15. When you place an ice cube in a glass of warm water, what happens to the temperature of the water in the glass? Use the definitions of heat and temperature to explain why this happens.

16. A thermometer at room temperature is placed in a glass of cold water.

    (a) After the thermometer and water come to thermal equilibrium, how do their temperatures compare?

    (b) Does heat flow into the thermometer or out of the thermometer?

    (c) Does heat flow into the water or out of the water?

17. Suppose the glass from Exercise 16 contains only a few drops of cold water. Why is it impossible to accurately measure the initial temperature of the water with the thermometer?

18. The energy value of food is determined by burning a sample of the food and measuring the heat released. The energy rating assigned to the food is actually a kilocalorie (1000 calories), written as a Calorie (with a capital C). Thus,

    1 Calorie = 1 kilocalorie.

    (a) The nutrition facts for a popular brand of cookie are shown at the right. How many Calories are in one of these cookies?

    (b) How many calories of heat would be released from burning one of the cookies?

Nutrition Facts

Serving Size 3 Cookies (33g)
Servings Per Container About 45

Amount Per Serving	
Calories 160 Calories from Fat 60	
	% Daily Value*
Total Fat 7g	**11%**
Saturated Fat 1.5g	**7%**
Polyunsaturated Fat 0.5g	
Monounsaturated Fat 3g	
Cholesterol 0mg	**0%**
Sodium 200mg	**9%**
Total Carbohydrate 23g	**8%**
Dietary Fiber 1g	**4%**
Sugars 13g	
Protein 1g	

19. A car’s engine block is made of iron and has a mass of 210 kg. How much heat is absorbed by the engine block when its temperature is raised from 20°C to 90°C?

20. You are measuring the specific heat of tungsten. You heat a 215-gram sample of the metal to 100°C and place the sample in 450 grams of water at 20°C. The tungsten and water reach an equilibrium temperature of 21.5°C. What is the specific heat of the tungsten?

21. A 25-gram sample of ice has a temperature of –10°C. How much heat is needed to convert the ice into steam?