Measuring Energy Changes

14.3

Section Preview/ Specific Expectations

In this section, you will

- **explain** how mass, specific heat capacity, and change in temperature of an object determine how much heat the object gains or loses
- **solve** problems using the equation $Q = mc\Delta T$
- **communicate** your understanding of the following terms: *thermal energy*, *heat*, *temperature*, ΔT, *specific heat capacity*

You have probably had plenty of experience with heating and cooling materials around you. You know how to cool yourself by taking a cold shower. You know how to heat hot chocolate on a stove. However, have you ever stopped to think about what energy changes are occuring? Where does the energy come from, and where does it go?

Figure 14.9 **Suppose that you are very thirsty, but the tap water is not cold enough. How can you get the water as cold as you want it to be? Your experience tells you to add ice to the water. How does the ice cool the water?**

Any time that something is cooled or heated, a change in thermal energy occurs. **Thermal energy** is the kinetic energy of particles of matter. In a glass of tap water with ice (as shown in Figure 14.9), the water started out warmer than the ice. Energy was transferred from the water to the ice. As the ice absorbed the energy, the ice melted. As the water lost energy, the water cooled.

These examples involve heat. **Heat** is the transfer of thermal energy between objects with different temperatures. In this section, you will study how to measure the quantity of thermal energy that is transferred during a process involving an energy change.

CHECKPOINT

What other forms of energy can you think of? Make a list, starting with thermal energy.

Important Factors in Energy Measurement

How can you measure the change in energy when you add ice to water? **Temperature** is a measure of the average kinetic energy of a system. You have already had experience using a thermometer to measure temperature. By placing a thermometer in the water, you can monitor the drop in temperature when the ice is added. Temperature is an important factor in heat energy changes. What other factors are important? Work through the following ThoughtLab to find out.

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How does drinking hot chocolate warm you? Describe the energy transfer that takes place.

ThoughtLab Factors in Heat Transfer

Two students performed an experiment to determine what factors need to be considered when determining the quantity of thermal energy lost or gained by a substance undergoing an energy change. They set up their experiment as follows.

Part A

The students placed two different masses of water, at the same initial temperature, in separate beakers. They placed an equal mass of ice (from the same freezer) in each beaker. Then they monitored the temperature of each beaker. Their results are listed in the table below.

Different Masses of Water

Beaker	1	2
Mass of water (g)	60.0	120.0
Initial temperature of water (°C)	26.5	26.5
Mass of ice added (g)	10.0	10.0
Final temperature of mixture (°C)	9.7	17.4
Temperature change (°C)	16.8	9.1

Part B

The students placed equal masses of canola oil and water, at the same initial temperature, in separate beakers. They placed equal masses of ice (from the same freezer) in the two beakers. Then they monitored the temperature of each beaker. Their results are listed in the following table.

Different Liquids

Beaker	1 (canola oil)	2 (water)
Mass of liquid (g)	60.0	60.0
Initial temperature of liquid (°C)	35.0	35.0
Mass of ice added (g)	10.0	10.0
Final temperature of mixture (°C)	5.2	16.9
Temperature change (°C)	29.8	18.1

Procedure

1. For each part of the experiment, identify
   (a) the variable that was changed by the students (the manipulated variable)
   (b) the variable that changed as a result of changing the manipulated variable (the responding variable)
   (c) the variables that were kept constant to ensure a fair test (the controlled variables)
2. Interpret the students' results by answering the following questions.
   (a) If ice is added to two different masses of water, how does the temperature change?
   (b) If ice is added to two different liquids, how does the temperature change?

Analysis

Think about your interpretation of the students' experiment and the discussion prior to this ThoughtLab. What are three important factors to consider when measuring the thermal energy change of a substance?

The ThoughtLab gave you some insight into the factors that are important when measuring energy changes. How can you use these factors to calculate the quantity of heat that is transferred? First you must examine each factor and determine its relationship to heat transfer. You will begin with the most obvious factor: temperature. Then you will look at how the mass of a substance affects the quantity of thermal energy it can store. Finally, you will look at the type of substance and how it affects heat transfer.

Temperature

In the summer, your body temperature is fairly close to the temperature of your surroundings. You do not need to wear extra clothing to keep warm. When winter hits with fierce winds and cold temperatures, however, dressing warmly becomes a necessity. The temperature of your surroundings is now much colder than your body temperature. Heat is transferred from your body to your surroundings, making you feel cold. The extra clothing helps to minimize heat loss from your body. (See Figure 14.10.)

Temperature is directly related to heat transfer. A large change in temperature indicates a large energy change. A small change in temperature indicates a small energy change. Therefore, temperature is an important factor when calculating heat transfer. The temperature variable that is used is the *change in temperature*. This is symbolized by ΔT.

Figure 14.10 How do you control the temperature of your body?

Mass of Substance

Did you know that 70% of Earth's surface is covered with water? This enormous mass of water absorbs and releases tremendous amounts of heat energy. Water makes our climate more moderate by absorbing heat in hot weather and releasing heat in cold weather. The greater the mass of the water, the greater the amount of heat it can absorb and release. (Areas without much water, such as deserts, experience huge variations in temperature.) Therefore, mass is directly related to heat transfer. Mass is a variable in the calculation of heat energy. It is symbolized by a lower-case m.

Type of Substance

In the ThoughtLab on page 594, you probably noticed that the quantity of heat being transferred depends on the type of substance. When you added equal masses of ice to the same mass of oil and water, the temperature change of the oil was almost double the temperature change of the water. "Type of substance" cannot be used as a variable, however, when calculating energy changes. Instead, we use a variable that reflects the individual nature of different substances: specific heat capacity. The **specific heat capacity** of a substance is the quantity of energy, in joules (J), that is required to change one gram (g) of the substance by one degree Celsius (°C). The specific heat capacity of a substance reflects how well the substance can store energy. A substance with a large specific heat capacity can absorb and release more energy than a substance with a smaller specific heat capacity. The symbol that is used for specific heat capacity is a lower-case c. The units are J/g·°C.

The specific heat capacity of water is relatively large: 4.184 J/g·°C. This value helps to explain how water can absorb and release enough energy to moderate Earth's temperature. Examine the values in Table 14.2. Notice that the specific heat capacities of most substances are much lower than the specific heat capacity of water.

Table 14.2 Specific Heat Capacities of Various Substances

Substance	Specific heat capacity (J/g·°C at 25°C)
Elements	
aluminum	0.900
carbon (graphite)	0.711
copper	0.385
gold	0.129
hydrogen	14.267
iron	0.444
Compounds	
ammonia (liquid)	4.70
ethanol	2.46
water (solid)	2.01
water (liquid)	4.184
water (gas)	2.01
Other materials	
air	1.02
concrete	0.88
glass	0.84
granite	0.79
wood	1.76

You have just considered three variables: change in temperature (ΔT), mass (m), and type of substance, which is characterized by specific heat capacity (c). How can you combine these variables into a formula to calculate heat transfer (Figure 14.11)?

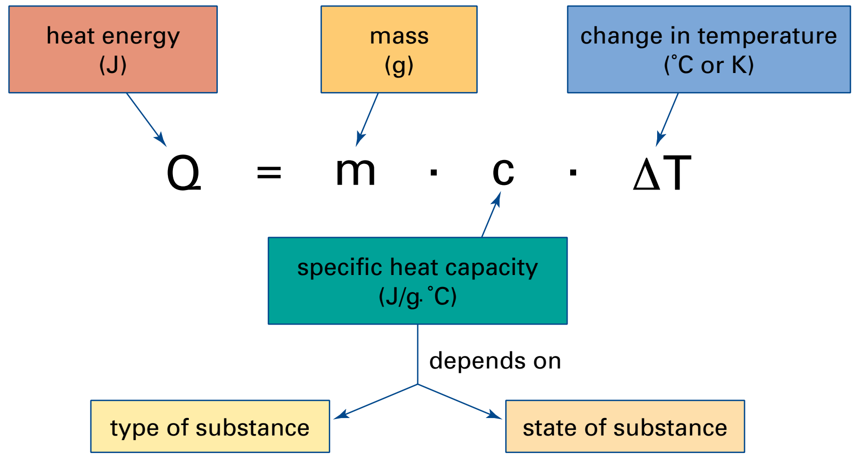

Figure 14.11 Use this formula to calculate heat (Q) transfer.

How do you solve heat energy problems using $Q = mc\Delta T$? Go back to the ThoughtLab. Some of the data in this ThoughtLab can be used to illustrate the calculation of heat transfer, as shown below.

Sample Problem

Heat Transferred From Water to Ice

Problem

In the ThoughtLab on page 594, 10.0 g of ice was added to 60.0 g of water. The initial temperature of the water was 26.5°C. The final temperature of the mixture was 9.7°C. How much heat was lost by the water?

What Is Required?

You need to calculate the quantity of heat (Q) that was lost by the water.

What Is Given?

You know the mass of the water. You also know the initial and final temperatures of the water.

Mass of water (m) = 60.0 g
Initial temperature (T_i) = 26.5°C
Final temperature (T_f) = 9.7°C

Plan Your Strategy

You have enough information to solve this problem using $Q = mc\Delta T$. Use the initial and final temperatures to calculate ΔT. You need the specific heat capacity (c) of liquid water. This is given in Table 14.2 (4.184 J/g·°C). Because you are only concerned with the water, you will not use the mass of the ice.

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Why does water have such a high specific heat capacity? Do some research to find out. **Hint**: Water's specific heat capacity has something to do with bonding.

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Act on Your Strategy

Substitute the values into the following heat formula, and solve. Remember that $\Delta T = T_f - T_i$

$$
\begin{aligned}
Q &= mc\Delta T \\
&= (60.0\ \text{g})\left(4.184\frac{\text{J}}{\text{g}\cdot{}^\circ\text{C}}\right)(9.7^\circ\text{C} - 26.5^\circ\text{C}) \\
&= -4217.472\ (\cancel{\text{g}})\left(\frac{\text{J}}{\cancel{\text{g}}\cdot\cancel{{}^\circ\text{C}}}\right)(\cancel{{}^\circ\text{C}}) \\
&= -4217.472\ \text{J} \\
&= -4.22 \times 10^3\ \text{J (or } -4.22\ \text{kJ)}
\end{aligned}
$$

The water lost 4.22×10^3 J of heat.

Check Your Solution

The water lost heat, so the heat value should be negative. Heat is measured in joules or kilojoules. Make sure that the units cancel out to give the appropriate unit for your answer.

Practice Problems

8. 100 g of ethanol at 25°C is heated until it reaches 50°C. How much heat does the ethanol gain? **Hint**: Find the specific heat capacity of ethanol in Table 14.2.

9. In Part A of the ThoughtLab on page 594, the students added ice to 120.0 g of water in beaker 2. Calculate the heat lost by the water. Use the information given for beaker 2, as well as specific heat capacities in Table 14.2.

10. A beaker contains 50 g of liquid at room temperature. The beaker is heated until the liquid gains 10°C. A second beaker contains 100 g of the same liquid at room temperature. This beaker is also heated until the liquid gains 10°C. In which beaker does the liquid gain the most thermal energy? Explain.

11. As the diagram on the next page illustrates, the sign of the heat value tells you whether a substance has lost or gained heat energy. Consider the following descriptions. Write each heat value, and give it the appropriate sign to indicate whether heat was lost or gained.

(a) In Part A of the ThoughtLab on page 594, the ice gained the heat that was lost by the water. When ice was added to 60.0 g of water, it gained 4.22 kJ of energy. When ice was added to 120.0 g of water, it gained 4.6 kJ of energy.

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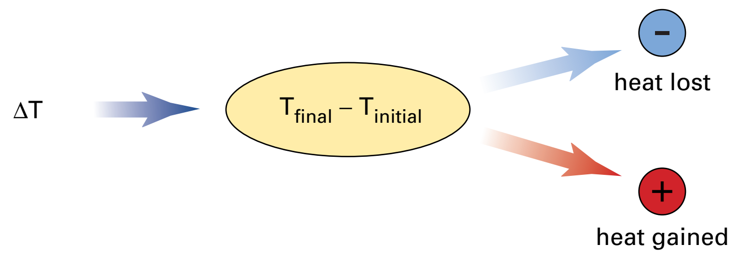

(b) When 2.0 L of water was heated over a campfire, the water gained 487 kJ of energy.

(c) A student baked a cherry pie and put it outside on a cold winter day. There was a change of 290 kJ of heat energy in the pie.

Math LINK

Heat values are often very large. Therefore it is convenient to use kilojoules (kJ) to calculate heat. How does this affect the units of the other variables in the heat equation? Does the specific heat capacity have to change? The following diagram shows how units must be modified in order to end up with kilojoules.

$$Q = m \cdot c \cdot \Delta T$$

Units: → $\mathrm{kJ} = \mathrm{kg} \cdot \dfrac{4.184\ \mathrm{kJ}}{\mathrm{kg} \cdot {}^{\circ}\mathrm{C}}\ {}^{\circ}\mathrm{C}$

mass-must be kg

Specific heat capacity
- must have kJ (top) and kg (bottom)
- Since "k" is on top andbottom, the number stays the same

In the Sample Problem, heat was *lost* by the water. Therefore the value of Q was *negative*. If the value of Q is *positive*, this indicates that heat is *gained* by a substance.

The heat equation $Q = mc\Delta T$ can be rearranged to solve for any of the variables. For example, in Part B of the ThoughtLab on page 594, ice was added to both canola oil and water. How can you use the information given in Part B to calculate the specific heat capacity of the canola oil?

Figure 14.12 **Canola oil is a vegetable oil that is used in salads and cooking.**

Sample Problem

Calculating Specific Heat Capacity

Problem

Calculate the specific heat capacity of canola oil, using the information given in Part B of the ThoughtLab on page 594. Note that the ice gained 4.0×10^3 J of energy when it came in contact with the canola oil.

What Is Required?

You need to calculate the specific heat capacity (c) of the canola oil.

What Is Given?

From the ThoughtLab, you know the mass (m) and the initial and final temperatures of the canola oil.

Mass of oil (m) = 60.0 g

Initial temperature (T_i) = 35.0°C

Final temperature (T_f) = 5.2°C

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You also know the quantity of heat gained by the ice. This must be the same as the heat lost by the oil.
Heat gained by the ice = Heat lost by the canola oil = 4.0×10^3 J

Plan Your Strategy

Rearrange the equation $Q = mc\Delta T$ to solve for c. Then substitute the values for Q, m, and ΔT ($T_f - T_i$) into the equation.

Act on Your Strategy

$$\begin{aligned} c &= \frac{Q}{m\Delta T} \\ &= \frac{-4.0 \times 10^3 \text{ J}}{(60.0 \text{ g})(5.2^\circ\text{C} - 35.0^\circ\text{C})} \\ &= 2.2437 \frac{\text{J}}{\text{g}\cdot{}^\circ\text{C}} \\ &= 2.24 \frac{\text{J}}{\text{g}\cdot{}^\circ\text{C}} \end{aligned}$$

Check Your Solution

The specific heat capacity should be positive, and it is. It should have the units $\frac{\text{J}}{\text{g}\cdot{}^\circ\text{C}}$.

Practice Problems

12. Solve the equation $Q = mc\Delta T$ for the following quantities.

(a) m

(b) c

(c) ΔT

13. You know that $\Delta T = T_f - T_i$. Combine this equation with the heat equation, $Q = mc\Delta T$, to solve for the following quantities.

(a) T_i (in terms of Q, m, c, and T_f)

(b) T_f (in terms of Q, m, c, and T_i)

14. How much heat is required to raise the temperature of 789 g of liquid ammonia, from 25.0°C to 82.7°C?

15. A solid substance has a mass of 250.00 g. It is cooled by 25.00°C and loses 4937.50 J of heat. What is its specific heat capacity? Look at Table 14.2 to identify the substance.

16. A piece of metal with a mass of 14.9 g is heated to 98.0°C. When the metal is placed in 75.0 g of water at 20.0°C, the temperature of the water rises by 28.5°C. What is the specific heat capacity of the metal?

17. A piece of gold (c = 0.129 J/g°C) with mass of 45.5 g and a temperature of 80.5°C is dropped into 192 g of water at 15.0°C. What is the final temperature of the system? (**Hint:** Use the equation $Q_w = -Q_g$.)

In this section, you learned that temperature, mass, and type of substance are all important factors to consider when measuring heat change. You saw how these factors can be combined to produce the heat equation:

$$Q = mc\Delta T$$

In the next section, you will learn how to use a calorimeter to measure heat change. You will perform a heat transfer investigation of your own. Using the knowledge you have gained in this section, you will then calculate the specific heat capacity. As well, you will see why the Procedure that was used in the ThoughtLab could be improved.

Section Review

1. K/U Define the term "heat."

2. I What are three important factors to consider when measuring heat energy?

3. I In Part B of the ThoughtLab, 60.0 g of water was in beaker 2. The initial temperature of the water was 35.0°C, and the final temperature was 16.9°C.
   - **(a)** Calculate the heat that was lost by the water in beaker 2.
   - **(b)** Where did the heat go?

4. I When iron nails are hammered into wood, friction causes the nails to heat up.
   - **(a)** Calculate the heat that is gained by a 5.2 g iron nail as it changes from 22.0°C to 38.5°C. (See Table 14.2.)
   - **(b)** Calculate the heat that is gained by a 10.4 g iron nail as it changes from 22.0°C to 38.5°C.
   - **(c)** Calculate the heat that is gained by the 5.2 g nail if its temperature changes from 22.0°C to 55.0°C.

5. **(a)** I A 23.9 g silver spoon is put in a cup of hot chocolate. It takes 0.343 kJ of energy to change the temperature of the spoon from 24.5°C to 85.0°C. What is the specific heat capacity of solid silver?
   - **(b)** I The same amount of heat energy, 0.343 kJ, is gained by 23.9 g of liquid water. What is the temperature change of the water?

6. C The specific heat capacity of aluminum is 0.902 J/g°C. The specific heat capacity of copper is 0.389 J/g°C. The same amount of heat is applied to equal masses of these two metals. Which metal increases more in temperature? Explain.

7. K/U Explain why there is an energy difference between the following reactions.

$$CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(g)} + 802 \text{ kJ}$$
$$CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(\ell)} + 890 \text{ kJ}$$