LESSON

5 The Heat Is On

Specific Heat Capacity

Think About It

Imagine you put a metal pan and a pizza in a hot oven. Both the pizza and the pan start out at room temperature. You leave them in the oven for the same amount of time. Will they heat up to the same temperature? And once they are taken out of the oven, will they cool off differently?

How do different substances respond to heat?

To answer this question, you will explore

① Specific Heat Capacity

② Bonding, Numbers, and Heat

Exploring the Topic

① Specific Heat Capacity

Every substance has a unique response to heat. Suppose you place an aluminum pot of water on the stove to heat. After a minute, the metal pot will be too hot to touch, but the water will still be cool. This is because different amounts of energy are needed to raise the temperature of each type of substance.

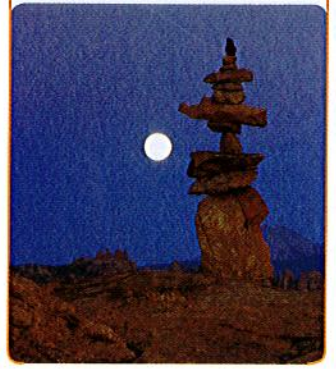
To compare heat transfer to different substances, you can measure the energy required to raise the temperature of the same mass of each substance by the same number of degrees. The amounts of energy needed to raise the temperature of 1 g of several sample substances by 1 °C are given in the table.

Sample	Mass (g)	ΔT (°C)	Energy required (cal)
water, $H_2O(l)$	1.0 g	1 °C	1.0 cal
methanol, $CH_3OH(l)$	1.0 g	1 °C	0.58 cal
aluminum, $Al(s)$	1.0 g	1 °C	0.21 cal
copper, $Cu(s)$	1.0 g	1 °C	0.09 cal

Notice that fewer calories of energy are required to raise the temperature of methanol, aluminum, and copper from 20 °C to 21 °C, compared with water. This is consistent with the observation that the aluminum pot heats up and cools off faster than the water in the pot. Less energy is involved in changing the temperature of the aluminum.

ENVIRONMENTAL CONNECTION

Deserts can be extremely hot at midday and extremely cold at night. The lack of water vapor in the air allows for greater temperature fluctuations. As a result, near the coast summers are not as hot and winters are not as cold as they are farther inland.



The heat required to raise the temperature of 1 g of a substance by 1 °C is called the **specific heat capacity.** Every substance has a specific heat capacity. Some values are shown in the table.

Substance	Specific heat capacity (cal/g · °C)
aluminum, Al(s)	0.21
water, $H_2O(l)$	1.00
copper, Cu(s)	0.09
iron, Fe(s)	0.11
wood (cellulose), $(C_6H_{10}O_5)_n(s)$	0.41
glass, $SiO_2(s)$	0.16
nitrogen, $N_2(g)$	0.24
ethanol, $CH_3CH_2OH(l)$	0.57
hydrogen, $H_2(g)$	3.34

The greater the specific heat capacity of a substance, the less its temperature will rise when it absorbs a given amount of energy. If a substance has a low specific heat capacity, it will change temperature easily, with a small transfer of energy. This applies whether the energy is being transferred into or out of the substance. This is why the aluminum pot heats up faster, and also cools down faster, than water. Water does not change temperature as easily as most substances.

BIG IDEA Substances with low specific heat capacities can heat up and cool down easily.

q= heat transfer

The specific heat capacity of a substance can be used to determine the amount of energy needed to raise the temperature of any mass by any number of degrees. The formula for heat transfer to any substance is a product of the mass, m, its specific heat capacity, C_p, and the temperature change, ΔT.

$$q = mC_p\Delta T$$

Example 1

Cooling

Suppose you have 15 g of methanol, CH_3OH, and 15 g of water, H_2O, both at 75 °C. You want to cool both samples to 20 °C. How much energy (in calories) do you need to remove from each sample?

Solution

The energy transferred is a product of the mass, the specific heat capacity, and the change in temperature.

$$q = mC_p\Delta T$$

The mass of each sample is 15 g, and the change in temperature is 20 °C minus 75 °C, or −55 °C. However, the specific heat capacities of water and methanol are different. The specific heat capacity of water is 1 cal/g · °C. The specific heat capacity of methanol is 0.58 cal/g · °C.

Water:

$$q = (15\text{ g})(1\text{ cal/g}\cdot{}^\circ\text{C})(-55\ {}^\circ\text{C}) = -830\text{ cal}$$

Methanol:

$$q = (15\text{ g})(0.58\text{ cal/g}\cdot{}^\circ\text{C})(-55\ {}^\circ\text{C}) = -480\text{ cal}$$

It takes a greater transfer of energy to cool water than to cool methanol. Because of this, water is a very good insulator and retains its temperature.

Example 2

Final Temperature

Imagine that you have 3.5 g of copper and 3.5 g of water. Both are at 25 °C. Which sample will be at a higher temperature if you transfer 150 cal to each? Show your work.

Solution

The energy transferred is a product of the mass, the specific heat capacity, and the change in temperature.

$$q = mC_p\Delta T$$

You know the value of q and the masses of the water and copper samples. You want to find the temperature change. Solve for ΔT. You can rearrange the equation:

$$\Delta T = \frac{q}{mC_p}$$

You can look up the specific heat capacities of water and copper in a table like the one on page 494. The specific heat capacity of water is 1 cal/g · °C. The specific heat capacity of copper is 0.09 cal/g · °C.

Water:

$$\Delta T = \frac{q}{mC_p} = \frac{150\text{ cal}}{(3.5\text{ g})(1\text{ cal/g}\cdot{}^\circ\text{C})} = 43\ {}^\circ\text{C}$$

Copper:

$$\Delta T = \frac{q}{mC_p} = \frac{150\text{ cal}}{(3.5\text{ g})(0.09\text{ cal/g}\cdot{}^\circ\text{C})} = 480\ {}^\circ\text{C}$$

The temperature of copper rises about ten times as much as the temperature of the same quantity of water when 150 calories of energy are transferred.

To find the final temperature, add the temperature change to the initial temperature.

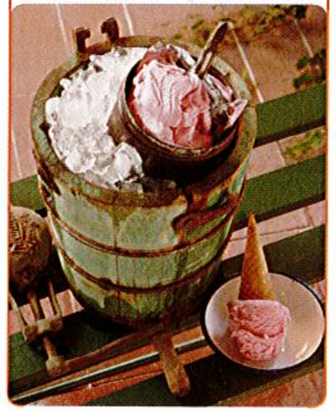
Water: Final temperature = 25 °C + 43 °C = 68 °C

Copper: Final temperature = 25 °C + 480 °C = 505 °C

For the same amount of heat transfer, the copper is much hotter.

CONSUMER CONNECTION

In order to make ice cream, the ingredients must be mixed at below freezing temperature. This is why you add salt to the ice in the outermost chamber of an ice-cream maker. Salt causes the ice to melt because salt water has a lower freezing point than water. However, it requires energy to melt ice, so heat is transferred from the ice cream to the salt-ice mixture, lowering the temperature to below 0 °C.



② Bonding, Numbers, and Heat

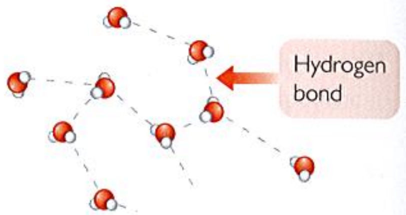
It may seem strange that different amounts of energy are needed to raise the temperature of different substances. Why would you need more energy for water, compared with the same mass of methanol, aluminum, or copper to heat them all to the same temperature?

The answer is partially related to molar mass. Look back at the table of specific heat capacities. While the molar mass of aluminum is 27.0 g/mol, the molar mass of copper is 63.6 g/mol. So, there are more atoms in 1 g of aluminum than in 1 g of copper. It makes sense that more energy is required to cause a larger number of atoms to move faster.

Bonding also has an effect on the specific heat capacity of a substance. Substances that are polar tend to have high specific heat capacities. This means that molecules will have higher specific heat capacities than metals.

Finally, complicated molecules with large numbers of atoms have a variety of internal vibrational motions. The atoms within the molecule can vibrate back and forth like balls on a spring. And the entire molecule can rotate. All of these motions need to be increased in order to raise the temperature. So, substantially more heat is required to increase the average kinetic energy of molecules compared with individual atoms.

High Specific Heat Capacity of Water



Water has a particularly high specific heat capacity for several reasons. First, the molar mass of water, 18.0 g/mol, is quite small. So there are a lot of water molecules to get moving in a 1 g sample. Second, because water is molecular, it has complex internal movements. Third, water consists of H_2O molecules with strong intermolecular attractions called **hydrogen bonds.** A hydrogen bond is the attraction between the positive and negative dipoles of different water molecules. The hydrogen bonding restricts the motions of the molecules. Extra heat needs to be added in order to overcome these attractions and raise the kinetic energy. This is why the water in the metal pot heats up so much more slowly than the metal pot itself.

Key Terms

specific heat capacity
hydrogen bond

Lesson Summary

How do different substances respond to heat?

In order to increase the temperature of a sample of matter, you must supply energy to it. But the addition of a given amount of energy does not always result in the same rise in temperature. Substances differ in their responses to heat. Some substances, like metals, change temperature more than others in response to the transfer of the same amount of energy. This is because they have a lower specific heat capacity. Specific heat capacity is the amount of energy needed to raise the temperature of 1 g of a substance by 1 °C. The specific heat capacity of a substance depends on a number of factors, including the number of atoms or molecules in a sample and the type of bonding.

EXERCISES

Reading Questions

1. What is specific heat capacity? Give the specific heat capacity of a substance, and explain what that means in terms of that substance.
2. Why is more energy required to raise the temperature of 1.0 g of water compared with 1.0 g of aluminum?

Reason and Apply

5. Use specific heat capacity to explain why metal keys left in the sun are hotter than a plastic pair of sunglasses left in the sun.
6. How much energy is required to raise the temperature of 50 g of methanol from 20 °C to 70 °C?
7. If you place 20 g of aluminum and 20 g of copper, both at 20 °C, into ice water, which will cool faster? Explain.
8. Imagine you have 50 g of water and 50 g of methanol, each in a 100 mL beaker. You place both on a hot plate on low heat.

   b. If the initial temperature of each liquid is 23 °C, what is the temperature of each after 25 cal of energy are transferred from the hot plate to each sample.

LESSON

8 Now We're Cooking

Calorimetry

Think About It

Foods are sources of energy, and certain foods are better sources of energy than others. What are the energy differences between a granola bar, a handful of nuts, and a few potato chips? Burning dry food items is one way to discover the possible energy potential of each type of food.

How are food Calories measured?

To answer this question, you will explore

1. Foods As Fuel
2. Calorimetry

Exploring the Topic

① Foods As Fuel

The foods you eat are sources of energy. There are no fires in your stomach, but your body processes the food you eat to generate energy. Burning two foods and comparing the energy transfer that results is a way to measure the energy of each food.

Food Calories

Food labels contain a wide variety of nutritional data, including Calorie content, which is a measure of energy. Food Calories, or Calories with a capital C, are actually kilocalories of energy, abbreviated kcal or Cal. This product label tells you that 1 ounce of potato chips has 160 Cal. In comparison, 1 ounce of walnuts has 190 Cal.

Nutrition Facts

Serving Size 1 oz.

Amount Per Serving

Calories 160 Calories from fat 80

	% Daily Value*
Total Fat 10g	16%
Saturated Fat 1g	5%
Polyunsaturated Fat 3g	
Monounsaturated Fat 6g	
Trans Fat 0g	
Cholesterol 0mg	0%
Sodium 160mg	7%
Potassium 340mg	10%
Total Carbohydrate 14g	5%
Dietary Fiber 1g	4%
Sugars 0g	
Protein 2g	

Vitamin A 0% • Vitamin C 10%

Calcium 0% • Iron 0%

Vitamin E 8% • Thiamin 2%

Niacin 4% • Vitamin B_6 6%

Phosphorus 4%

*Percent Daily Values are based on a 2,000 calorie diet. Your daily values may be higher or lower depending on your calorie needs:

	Calories	2,000	2,500
Total Fat	Less than	65g	80g
Sat Fat	Less than	20g	25g
Cholesterol	Less than	300mg	300mg
Sodium	Less than	2,400mg	2,400mg
Potassium		3,500mg	3,500mg
Total Carbohydrate		300g	375g
Dietary Fiber		25g	30g

Calories per gram:
Fat g • Carbohydrate 4 • Protein 4

Example

Comparing Calories per Gram

Are there more Calories in 1.0 g of potato chips or 1.0 g of walnuts? (28.3 g = 1.0 oz)

Solution

There are 160 Cal in 1.0 oz of potato chips. There are 190 Cal in 1.0 oz of walnuts. An ounce is the same as 28.3 g.

$$\text{Potato chips: } 160 \text{ Cal}/28.3 \text{ g} = 5.6 \text{ Cal/g}$$

$$\text{Walnuts: } 190 \text{ Cal}/28.3 \text{ g} = 6.7 \text{ Cal/g}$$

So, there are more Calories available in 1.0 g of walnuts than 1.0 g of potato chips.

According to these calculations, an ounce of walnuts contains more energy than an ounce of potato chips. However, the number of Calories per gram is fairly close. In contrast, raisins contain 3.0 Cal per gram, and raw carrots contain 0.4 Cal per gram.

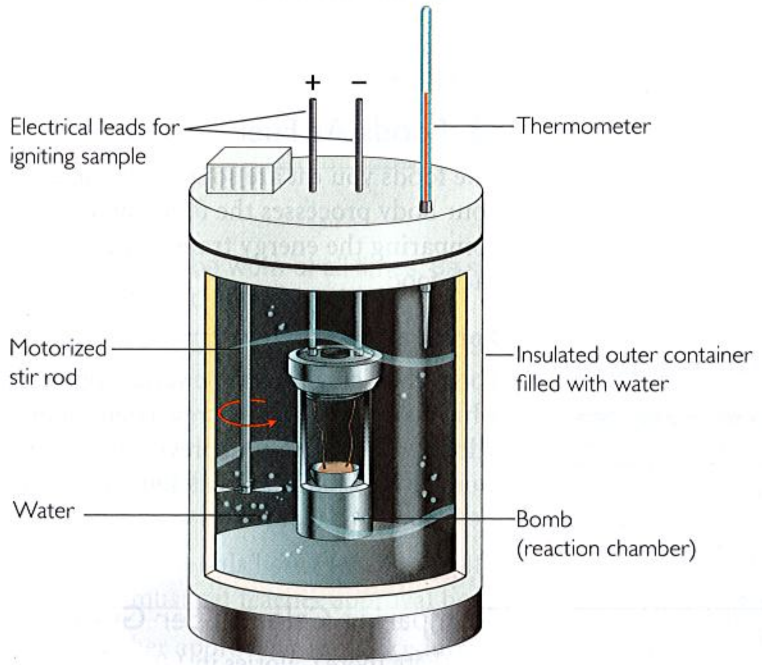
② Calorimetry

To measure the Calories in food, you need to find out how much energy the food can release when it reacts with oxygen. One way to determine the amount of heat transfer during a combustion reaction is to use the fuel to heat a measured amount of some other substance, such as water. You can then use a thermometer to measure the change in temperature of the water. The science of measuring the energy released or absorbed in a chemical reaction or physical change is called **calorimetry.** (In Latin, *calor* means heat and *meter* means measure.) Chemists and nutritionists alike use a bomb calorimeter to figure out the calorie content of combustible substances.

HEALTH CONNECTION

A healthy diet for the average adult consists of an intake of about 2000 food Calories per day. One fast-food double cheeseburger contains about 750 Calories, a medium soda is about 210 Calories, and a medium order of French fries is 450 Calories. If you ate this for lunch, you would have only 600 Calories left for the rest of the day.

The illustration shows a bomb calorimeter. The combustion reaction takes place in an inner reaction chamber called a bomb, which is completely surrounded by water. The sample is ignited by electrical energy, and the energy, due to the burning of the fuel, is transferred to the water. A stirring rod makes sure the heat is uniform in the water. If you determine the change in temperature of the water and you know the quantity of water in the calorimeter, you can determine the heat transferred during the combustion reaction.



Key Terms

calorimetry

Lesson Summary

How are food Calories measured?

There are a number of different ways to compare the energy of foods. Some foods can be burned and then their energies can be measured and compared. Calorimetry is the science of measuring the energy released or absorbed by a chemical or physical change. You can use a bomb calorimeter to measure the amount of heat transferred to the surroundings in a combustion reaction.

EXERCISES

Reading Questions

2. Why does a bomb calorimeter have an inner chamber and an outer chamber?

Reason and Apply

3. Can you measure the heat energy of a combustion reaction by placing a thermometer directly into the flames? Explain.

4. What is calorimetry?

5. Most school laboratories do not have bomb calorimeters.

  a. Design an experiment that would allow you to compare whether a cheese puff snack or a roasted corn snack transfers more energy when burned.

  b. In your experiment, does it matter whether you burn the same mass of cheese puff and roasted corn snack? Why or why not?

  c. Why is it important to measure the mass of each snack food at the end of your experiment?

  d. What are some possible sources of error that could occur in your experiment?

LESSON
9 Counting Calories
Calorimetry Calculations

Think About It

Heating a beaker of water with a burning potato chip seems like an unusual way to determine the number of Calories in this snack food. However, this is very close to the actual procedure used by nutritionists.

How does a calorimetry experiment translate into Calories?

To answer this question, you will explore

① Calorimetry in the Lab
② Calorimetry Calculations

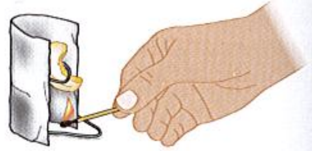
Exploring the Topic

① Calorimetry in the Lab

Suppose you wanted to measure the amount of energy transfer from combustion of a cashew nut. Because the digestive processes of the human body cannot be duplicated in your classroom, the next best approach is to determine the energy that can be transferred when food reacts directly with oxygen. To do this, you need to burn the food item and transfer the energy released due to combustion to another substance. Many substances can be used, but the most common one to use is water.

HEALTH CONNECTION

The actual amount of energy a human obtains after the digestive processes are completed is about 85% of the Calorie content listed on nutrition labels. Fats have high food energy densities, around 9 Cal/g. Sugars and proteins are around 4 Cal/g.



Building a shield of some sort helps to direct the heat from burning.

One feature of this type of experiment that is difficult to control in the lab is heat transfer to the surrounding air and equipment. Not all of the energy from burning is transferred directly to the water. Some thermal energy is transferred to the container, to the air, and even to you. One way to control this loss of energy is to burn the food sample very close to the bottom of the water container. Another way is to create some sort of shield to keep the energy transfer focused on the water. All of these details must be taken into account when designing a procedure.

② Calorimetry Calculations

There are three measurements and one property that help you to determine the energy transferred during a calorimetry procedure.

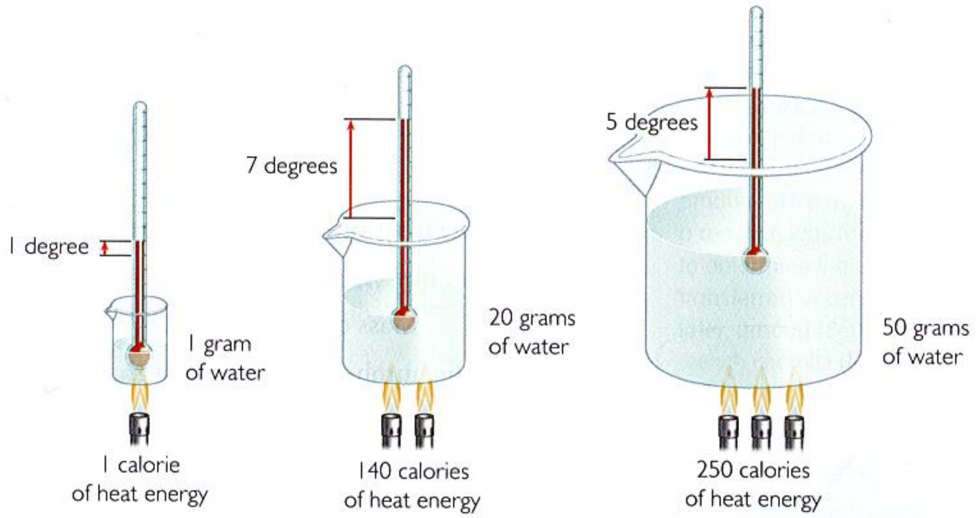
Data needed:

1. Mass of water heated in grams; 1 mL = 1 g
2. Temperature change of the water in degrees Celsius, ΔT (delta T)
3. Mass of fuel burned in grams
4. Specific heat capacity of water = 1.00 cal/g °C at 25 °C and 1 atm pressure

With the first two pieces of data, you can calculate how many calories of thermal energy are transferred to the water. Recall that the equation for heat transfer is

$$q = mC_p\Delta T$$

where C_p is the specific heat capacity of the substance being heated.



The number of calories of energy transferred is dependent on the mass of the water and the temperature change.

The illustration shows that if you multiply the change in temperature by the mass of the water, you can calculate the number of calories of heat transferred to the water. This is because the specific heat capacity of water is 1.00 cal/g · °C.

Example 1

Calories from a Cashew

These data were collected from the burning of one cashew. How much thermal energy was transferred?

Initial T of water = 19.0 °C

Final T of water = 34.5 °C

Volume of water = 30.0 mL

Solution

First, figure out the temperature change.

Subtract the initial temperature from the final temperature.

$$\Delta T = 34.5\ ^\circ\text{C} - 19.0\ ^\circ\text{C} = 15.5\ ^\circ\text{C}$$

Since 1 mL of water is equal to 1.0 g of water, the mass of the water heated is 30.0 g.

Use the equation for heat transfer.

Substitute values and solve.

$$q = mC_p\Delta T = 30.0\text{ g}(1.00\text{ cal/g}\cdot{}^\circ\text{C})15.5\ ^\circ\text{C} = 465\text{ cal}$$

One cashew transferred 435 cal of energy to the water. In order to compare different foods, it is necessary to figure out the calories *per gram* of food burned.

Example 2

Calories per Gram of Cashew

How much energy per gram was released by the combustion of the cashew?

$$\text{Initial mass of cashew} = 0.66 \text{ g}$$

$$\text{Final mass of cashew} = 0.06 \text{ g}$$

Solution

Figure out the mass of the cashew burned.

Subtract final mass from initial mass.

$$\text{Mass of cashew burned} = 0.66 \text{ g} - 0.06 \text{ g} = 0.60 \text{ g}$$

Determine the number of calories per gram.

$$465 \text{ cal}/0.60 \text{ g} = 775 \text{ cal/g}$$

The number of calories per gram is also called the food energy density. Cashews have an energy density of 775 cal/g of cashew burned. Remember, these are chemist's calories. To convert them to food Calories, you must divide by 1000 to get 0.775 Cal/g.

Comparing Foods

In the real world, nutritionists use calorimeters to figure out the Calorie content of foods. The word *content* is misleading. The food does not actually contain the Calories. The Calorie content represents the energy transferred specifically by *combustion* of these compounds.

Bomb calorimeters minimize the heat transfer to the surroundings, and the results are much more precise than our lab experiments. The method of calculation is very similar to the one used here. If a bomb calorimeter is used, a cashew would be found to have closer to 5500 chemists' calories per gram, or 5.5 Cal/g. Our experimental results came up with 775 cal/g. There is a lot of error in the classroom procedure.

Lesson Summary

How does a calorimetry experiment translate into Calories?

Different fuels transfer different amounts of energy during a combustion reaction. The temperature change, fuel mass, and water volume data from a calorimetry procedure can be converted into Calories. Using the specific heat capacity of the substance that was heated by the reaction allows you to calculate the exact number of calories transferred by the combustion of the fuel. This provides you with a measure of the amount of thermal energy "contained" in a fuel. The number of calories transferred from a substance that burns depends on the identity of the substance and its mass.

EXERCISES

Reading Questions

1. Name three possible sources of error in a calorimetry experiment.

2. Why is it important to know the specific heat of the substance being heated by the combustion of a fuel?

Reason and Apply

3. Could you use ethanol instead of water in a calorimetry experiment? Explain.

5. A cereal flake is burned under a beaker containing 25 mL of water. If the water temperature goes up 6 °C, how many calories of energy were transferred to the water?

6. Fuel pellets are used in modern energy-saving wood stoves. If the pellets used for these stoves release 742 cal/g, how many calories of energy will be released by combustion of an entire 40 lb sack of pellets?

8. The calorie content of a peanut is measured by burning it beneath a can of water and measuring the temperature change of the water. Which of these is a possible source of error?

A. The initial mass of the peanut is measured incorrectly.

B. Some of the heat of combustion is transferred to the air.

C. Some unburned remnants of the peanut are lost before finding the final mass.

D. All of the above.

E. None of the above.

HISTORY CONNECTION

In the late 18th century, the French scientists Antoine Lavoisier and Pierre Laplace developed an ice calorimeter. With this apparatus, the amount of ice melted by a reaction was measured to determine the energy transferred. A century later, around 1860, the French chemist Pierre Bertholet constructed the first modern calorimeter.