a. a galvanometer
b. a manometer
c. a thermometer
d. a voltmeter

11.2 Heat, Specific Heat, and Heat Transfer

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Explain heat, heat capacity, and specific heat
- Distinguish between conduction, convection, and radiation
- Solve problems involving specific heat and heat transfer

Section Key Terms

conduction	convection	heat capacity	radiation	specific heat

Heat Transfer, Specific Heat, and Heat Capacity

We learned in the previous section that temperature is proportional to the average kinetic energy of atoms and molecules in a substance, and that the average internal kinetic energy of a substance is higher when the substance's temperature is higher.

If two objects at different temperatures are brought in contact with each other, energy is transferred from the hotter object (that is, the object with the greater temperature) to the colder (lower temperature) object, until both objects are at the same temperature. There is no net heat transfer once the temperatures are equal because the amount of heat transferred from one object to the other is the same as the amount of heat returned. One of the major effects of heat transfer is temperature change: Heating increases the temperature while cooling decreases it. Experiments show that the heat transferred to or from a substance depends on three factors—the change in the substance's temperature, the mass of the substance, and certain physical properties related to the phase of the substance.

The equation for heat transfer Q is

$$Q = mc\Delta T, \tag{11.7}$$

where m is the mass of the substance and ΔT is the change in its temperature, in units of Celsius or Kelvin. The symbol c stands for **specific heat**, and depends on the material and phase. The specific heat is the amount of heat necessary to change the temperature of 1.00 kg of mass by 1.00 °C. The specific heat c is a property of the substance; its SI unit is J/(kg ⋅ K) or J/(kg ⋅ $^\circ\text{C}$). The temperature change (ΔT) is the same in units of kelvins and degrees Celsius (but not degrees Fahrenheit). Specific heat is closely related to the concept of **heat capacity**. Heat capacity is the amount of heat necessary to change the temperature of a substance by 1.00 $^\circ\text{C}$. In equation form, heat capacity C is $C = mc$, where m is mass and c is specific heat. Note that heat capacity is the same as specific heat, but without any dependence on mass. Consequently, two objects made up of the same material but with different masses will have different heat capacities. This is because the heat capacity is a property of an object, but specific heat is a property of *any* object made of the same material.

Values of specific heat must be looked up in tables, because there is no simple way to calculate them. Table 11.2 gives the values of specific heat for a few substances as a handy reference. We see from this table that the specific heat of water is five times that of glass, which means that it takes five times as much heat to raise the temperature of 1 kg of water than to raise the temperature of 1 kg of glass by the same number of degrees.

Substances	Specific Heat (c)
Solids	J/(kg ⋅$^\circ\text{C}$)
Aluminum	900

Table 11.2 Specific Heats of Various Substances.

Substances	Specific Heat (*c*)
Asbestos	800
Concrete, granite (average)	840
Copper	387
Glass	840
Gold	129
Human body (average)	3500
Ice (average)	2090
Iron, steel	452
Lead	128
Silver	235
Wood	1700
Liquids	
Benzene	1740
Ethanol	2450
Glycerin	2410
Mercury	139
Water	4186
Gases (at 1 atm constant pressure)	
Air (dry)	1015
Ammonia	2190
Carbon dioxide	833
Nitrogen	1040
Oxygen	913
Steam	2020

Table 11.2 Specific Heats of Various Substances.

Snap Lab

Temperature Change of Land and Water

What heats faster, land or water? You will answer this question by taking measurements to study differences in specific heat capacity.

- Open flame—Tie back all loose hair and clothing before igniting an open flame. Follow all of your teacher's instructions on how to ignite the flame. Never leave an open flame unattended. Know the location of fire safety equipment in the laboratory.

- Sand or soil
- Water
- Oven or heat lamp
- Two small jars
- Two thermometers

Instructions

Procedure
1. Place equal masses of dry sand (or soil) and water at the same temperature into two small jars. (The average density of soil or sand is about 1.6 times that of water, so you can get equal masses by using 50 percent more water by volume.)
2. Heat both substances (using an oven or a heat lamp) for the same amount of time.
3. Record the final temperatures of the two masses.
4. Now bring both jars to the same temperature by heating for a longer period of time.
5. Remove the jars from the heat source and measure their temperature every 5 minutes for about 30 minutes.

GRASP CHECK

Did it take longer to heat the water or the sand/soil to the same temperature? Which sample took longer to cool? What does this experiment tell us about how the specific heat of water compared to the specific heat of land?

a. The sand/soil will take longer to heat as well as to cool. This tells us that the specific heat of land is greater than that of water.
b. The sand/soil will take longer to heat as well as to cool. This tells us that the specific heat of water is greater than that of land.
c. The water will take longer to heat as well as to cool. This tells us that the specific heat of land is greater than that of water.
d. The water will take longer to heat as well as to cool. This tells us that the specific heat of water is greater than that of land.

Conduction, Convection, and Radiation

Whenever there is a temperature difference, heat transfer occurs. Heat transfer may happen rapidly, such as through a cooking pan, or slowly, such as through the walls of an insulated cooler.

There are three different heat transfer methods: **conduction**, **convection**, and **radiation**. At times, all three may happen simultaneously. See Figure 11.3.

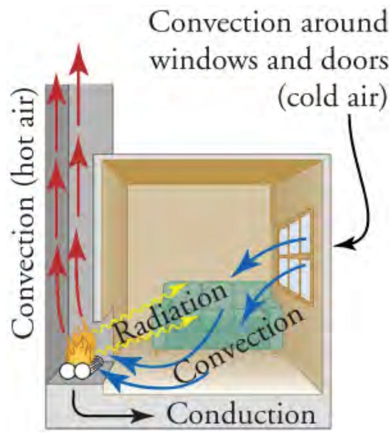


Figure 11.3 In a fireplace, heat transfer occurs by all three methods: conduction, convection, and radiation. Radiation is responsible for most of the heat transferred into the room. Heat transfer also occurs through conduction into the room, but at a much slower rate. Heat transfer by convection also occurs through cold air entering the room around windows and hot air leaving the room by rising up the chimney.

Conduction is heat transfer through direct physical contact. Heat transferred between the electric burner of a stove and the bottom of a pan is transferred by conduction. Sometimes, we try to control the conduction of heat to make ourselves more comfortable. Since the rate of heat transfer is different for different materials, we choose fabrics, such as a thick wool sweater, that slow down the transfer of heat away from our bodies in winter.

As you walk barefoot across the living room carpet, your feet feel relatively comfortable…until you step onto the kitchen's tile floor. Since the carpet and tile floor are both at the same temperature, why does one feel colder than the other? This is explained by different rates of heat transfer: The tile material removes heat from your skin at a greater rate than the carpeting, which makes it *feel* colder.

Some materials simply conduct thermal energy faster than others. In general, metals (like copper, aluminum, gold, and silver) are good heat conductors, whereas materials like wood, plastic, and rubber are poor heat conductors.

Figure 11.4 shows particles (either atoms or molecules) in two bodies at different temperatures. The (average) kinetic energy of a particle in the hot body is higher than in the colder body. If two particles collide, energy transfers from the particle with greater kinetic energy to the particle with less kinetic energy. When two bodies are in contact, many particle collisions occur, resulting in a net flux of heat from the higher-temperature body to the lower-temperature body. The heat flux depends on the temperature difference $\Delta T = T_{\text{hot}} - T_{\text{cold}}$. Therefore, you will get a more severe burn from boiling water than from hot tap water.

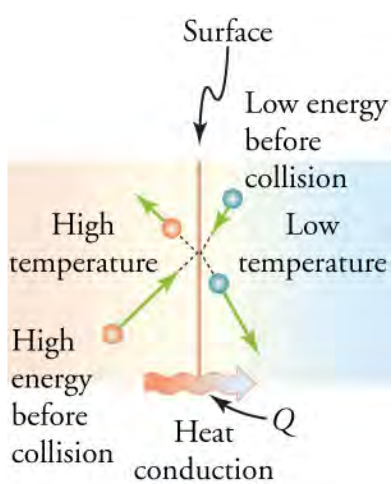


Figure 11.4 The particles in two bodies at different temperatures have different average kinetic energies. Collisions occurring at the contact surface tend to transfer energy from high-temperature regions to low-temperature regions. In this illustration, a particle in the lower-temperature region (right side) has low kinetic energy before collision, but its kinetic energy increases after colliding with the contact

surface. In contrast, a particle in the higher-temperature region (left side) has more kinetic energy before collision, but its energy decreases after colliding with the contact surface.

Convection is heat transfer by the movement of a fluid. This type of heat transfer happens, for example, in a pot boiling on the stove, or in thunderstorms, where hot air rises up to the base of the clouds.

TIPS FOR SUCCESS

In everyday language, the term *fluid* is usually taken to mean liquid. For example, when you are sick and the doctor tells you to "push fluids," that only means to drink more beverages—not to breath more air. However, in physics, fluid means a liquid *or a gas*. Fluids move differently than solid material, and even have their own branch of physics, known as *fluid dynamics*, that studies how they move.

As the temperature of fluids increase, they expand and become less dense. For example, Figure 11.4 could represent the wall of a balloon with different temperature gases inside the balloon than outside in the environment. The hotter and thus faster moving gas particles inside the balloon strike the surface with more force than the cooler air outside, causing the balloon to expand. This decrease in density relative to its environment creates buoyancy (the tendency to rise). Convection is driven by buoyancy—hot air rises because it is less dense than the surrounding air.

Sometimes, we control the temperature of our homes or ourselves by controlling air movement. Sealing leaks around doors with weather stripping keeps out the cold wind in winter. The house in Figure 11.5 and the pot of water on the stove in Figure 11.6 are both examples of convection and buoyancy by human design. Ocean currents and large-scale atmospheric circulation transfer energy from one part of the globe to another, and are examples of natural convection.

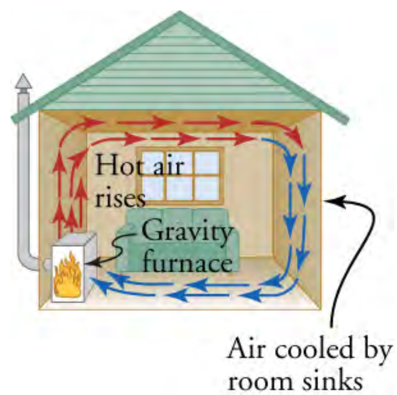


Figure 11.5 Air heated by the so-called gravity furnace expands and rises, forming a convective loop that transfers energy to other parts of the room. As the air is cooled at the ceiling and outside walls, it contracts, eventually becoming denser than room air and sinking to the floor. A properly designed heating system like this one, which uses natural convection, can be quite efficient in uniformly heating a home.

Figure 11.6 Convection plays an important role in heat transfer inside this pot of water. Once conducted to the inside fluid, heat transfer to other parts of the pot is mostly by convection. The hotter water expands, decreases in density, and rises to transfer heat to other regions of the water, while colder water sinks to the bottom. This process repeats as long as there is water in the pot.

Radiation is a form of heat transfer that occurs when electromagnetic radiation is emitted or absorbed. Electromagnetic radiation includes radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays, all of which have different wavelengths and amounts of energy (shorter wavelengths have higher frequency and more energy).

You can feel the heat transfer from a fire and from the sun. Similarly, you can sometimes tell that the oven is hot without touching its door or looking inside—it may just warm you as you walk by. Another example is thermal radiation from the human body; people are constantly emitting infrared radiation, which is not visible to the human eye, but is felt as heat.

Radiation is the only method of heat transfer where no medium is required, meaning that the heat doesn't need to come into direct contact with or be transported by any matter. The space between Earth and the sun is largely empty, without any possibility of heat transfer by convection or conduction. Instead, heat is transferred by radiation, and Earth is warmed as it absorbs electromagnetic radiation emitted by the sun.

Figure 11.7 Most of the heat transfer from this fire to the observers is through infrared radiation. The visible light transfers relatively little thermal energy. Since skin is very sensitive to infrared radiation, you can sense the presence of a fire without looking at it directly. (Daniel X. O'Neil)

All objects absorb and emit electromagnetic radiation (see Figure 11.7). The rate of heat transfer by radiation depends mainly on the color of the object. Black is the most effective absorber and radiator, and white is the least effective. People living in hot climates generally avoid wearing black clothing, for instance. Similarly, black asphalt in a parking lot will be hotter than adjacent patches of grass on a summer day, because black absorbs better than green. The reverse is also true—black radiates better than green. On a clear summer night, the black asphalt will be colder than the green patch of grass, because black radiates energy faster than green. In contrast, white is a poor absorber and also a poor radiator. A white object reflects nearly all radiation, like a mirror.

Virtual Physics

Energy Forms and Changes

Click to view content (http://www.openstax.org/l/28energyForms)

In this animation, you will explore heat transfer with different materials. Experiment with heating and cooling the iron, brick, and water. This is done by dragging and dropping the object onto the pedestal and then holding the lever either to Heat or Cool. Drag a thermometer beside each object to measure its temperature—you can watch how quickly it heats or cools in real time.

Now let's try transferring heat between objects. Heat the brick and then place it in the cool water. Now heat the brick again, but then place it on top of the iron. What do you notice?

Selecting the fast forward option lets you speed up the heat transfers, to save time.

GRASP CHECK

Compare how quickly the different materials are heated or cooled. Based on these results, what material do you think has the greatest specific heat? Why? Which has the smallest specific heat? Can you think of a real-world situation where you would want to use an object with large specific heat?

a. Water will take the longest, and iron will take the shortest time to heat, as well as to cool. Objects with greater specific heat would be desirable for insulation. For instance, woolen clothes with large specific heat would prevent heat loss from the body.

b. Water will take the shortest, and iron will take the longest time to heat, as well as to cool. Objects with greater specific heat would be desirable for insulation. For instance, woolen clothes with large specific heat would prevent heat loss from the body.
c. Brick will take shortest and iron will take longest time to heat up as well as to cool down. Objects with greater specific heat would be desirable for insulation. For instance, woolen clothes with large specific heat would prevent heat loss from the body.
d. Water will take shortest and brick will take longest time to heat up as well as to cool down. Objects with greater specific heat would be desirable for insulation. For instance, woolen clothes with large specific heat would prevent heat loss from the body.

Solving Heat Transfer Problems

WORKED EXAMPLE

Calculating the Required Heat: Heating Water in an Aluminum Pan

A 0.500 kg aluminum pan on a stove is used to heat 0.250 L of water from 20.0 $^{\circ}\mathrm{C}$ to 80.0 $^{\circ}\mathrm{C}$. (a) How much heat is required? What percentage of the heat is used to raise the temperature of (b) the pan and (c) the water?

STRATEGY

The pan and the water are always at the same temperature. When you put the pan on the stove, the temperature of the water and the pan is increased by the same amount. We use the equation for heat transfer for the given temperature change and masses of water and aluminum. The specific heat values for water and aluminum are given in the previous table.

Solution to (a)

Because the water is in thermal contact with the aluminum, the pan and the water are at the same temperature.

1. Calculate the temperature difference.

$$\Delta T = T_f - T_i = 60.0\ ^{\circ}\mathrm{C} \tag{11.8}$$

2. Calculate the mass of water using the relationship between density, mass, and volume. Density is mass per unit volume, or $\rho = \frac{m}{V}$. Rearranging this equation, solve for the mass of water.

$$m_w = \rho \cdot V = 1000\ \mathrm{kg/m^3} \times \left(0.250\ \mathrm{L} \times \frac{0.001\ \mathrm{m^3}}{1\ \mathrm{L}}\right) = 0.250\ \mathrm{kg} \tag{11.9}$$

3. Calculate the heat transferred to the water. Use the specific heat of water in the previous table.

$$Q_w = m_w c_w \Delta T = (0.250\ \mathrm{kg})(4186\ \mathrm{J/kg^{\circ}C})(60.0^{\circ}\mathrm{C}) = 62.8\ \mathrm{kJ} \tag{11.10}$$

4. Calculate the heat transferred to the aluminum. Use the specific heat for aluminum in the previous table.

$$Q_{Al} = m_{Al} c_{Al} \Delta T = (0.500\ \mathrm{kg})(900\ \mathrm{J/kg^{\circ}C})(60.0^{\circ}\mathrm{C}) = 27.0 \times 10^3\ \mathrm{J} = 27.0\ \mathrm{kJ} \tag{11.11}$$

5. Find the total transferred heat.

$$Q_{Total} = Q_w + Q_{Al} = 62.8\ \mathrm{kJ} + 27.0\ \mathrm{kJ} = 89.8\ \mathrm{kJ} \tag{11.12}$$

Solution to (b)

The percentage of heat going into heating the pan is

$$\frac{27.0\ \mathrm{kJ}}{89.8\ \mathrm{kJ}} \times 100\% = 30.1\% \tag{11.13}$$

Solution to (c)

The percentage of heat going into heating the water is

$$\frac{62.8\ \mathrm{kJ}}{89.8\ \mathrm{kJ}} \times 100\% = 69.9\% \tag{11.14}$$

Discussion

In this example, most of the total heat transferred is used to heat the water, even though the pan has twice as much mass. This is because the specific heat of water is over four times greater than the specific heat of aluminum. Therefore, it takes a bit more than twice as much heat to achieve the given temperature change for the water than for the aluminum pan.

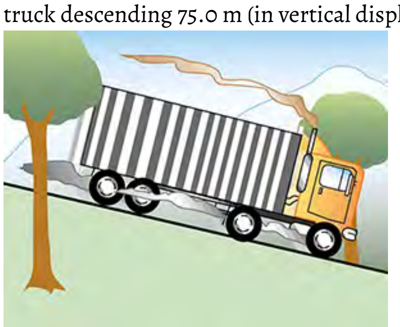
Water can absorb a tremendous amount of energy with very little resulting temperature change. This property of water allows for life on Earth because it stabilizes temperatures. Other planets are less habitable because wild temperature swings make for a harsh environment. You may have noticed that climates closer to large bodies of water, such as oceans, are milder than climates landlocked in the middle of a large continent. This is due to the climate-moderating effect of water's large heat capacity—water stores large amounts of heat during hot weather and releases heat gradually when it's cold outside.

WORKED EXAMPLE

Calculating Temperature Increase: Truck Brakes Overheat on Downhill Runs

When a truck headed downhill brakes, the brakes must do work to convert the gravitational potential energy of the truck to internal energy of the brakes. This conversion prevents the gravitational potential energy from being converted into kinetic energy of the truck, and keeps the truck from speeding up and losing control. The increased internal energy of the brakes raises their temperature. When the hill is especially steep, the temperature increase may happen too quickly and cause the brakes to overheat.

Calculate the temperature increase of 100 kg of brake material with an average specific heat of 800 J/kg $\cdot°\text{C}$ from a 10,000 kg truck descending 75.0 m (in vertical displacement) at a constant speed.



STRATEGY

We first calculate the gravitational potential energy (*Mgh*) of the truck, and then find the temperature increase produced in the brakes.

Solution

1. Calculate the change in gravitational potential energy as the truck goes downhill.

$$Mgh = (10,000\ \text{kg})\,(9.80\ \text{m/s}^2)\,(75.0\ \text{m}) = 7.35 \times 10^6\,\text{J} \tag{11.15}$$

2. Calculate the temperature change from the heat transferred by rearranging the equation $Q = mc\Delta T$ to solve for ΔT.

$$\Delta T = \frac{Q}{mc}, \tag{11.16}$$

where m is the mass of the brake material (not the entire truck). Insert the values $Q = 7.35 \times 10^6$ J (since the heat transfer is equal to the change in gravitational potential energy), $m = 100$ kg, and $c = 800$ J/kg $\cdot$ °C to find

$$\Delta T = \frac{7.35 \times 10^6\,\text{J}}{(100\ \text{kg})(800\ \text{J/kg}\ \cdot °\text{C})} = 91.9\ °\text{C}. \tag{11.17}$$

Discussion

This temperature is close to the boiling point of water. If the truck had been traveling for some time, then just before the descent, the brake temperature would likely be higher than the ambient temperature. The temperature increase in the descent would likely raise the temperature of the brake material above the boiling point of water, which would be hard on the brakes. This is why truck drivers sometimes use a different technique for called "engine braking" to avoid burning their brakes during steep descents. Engine braking is using the slowing forces of an engine in low gear rather than brakes to slow down.

Practice Problems

5. How much heat does it take to raise the temperature of 10.0 kg of water by 1.0 °C ?
   a. 84 J
   b. 42 J
   c. 84 kJ
   d. 42 kJ

6. Calculate the change in temperature of 1.0 kg of water that is initially at room temperature if 3.0 kJ of heat is added.
   a. 358 °C
   b. 716 °C
   c. 0.36 °C
   d. 0.72 °C

Check Your Understanding

7. What causes heat transfer?
   a. The mass difference between two objects causes heat transfer.
   b. The density difference between two objects causes heat transfer.
   c. The temperature difference between two systems causes heat transfer.
   d. The pressure difference between two objects causes heat transfer.

8. When two bodies of different temperatures are in contact, what is the overall direction of heat transfer?
   a. The overall direction of heat transfer is from the higher-temperature object to the lower-temperature object.
   b. The overall direction of heat transfer is from the lower-temperature object to the higher-temperature object.
   c. The direction of heat transfer is first from the lower-temperature object to the higher-temperature object, then back again to the lower-temperature object, and so-forth, until the objects are in thermal equilibrium.
   d. The direction of heat transfer is first from the higher-temperature object to the lower-temperature object, then back again to the higher-temperature object, and so-forth, until the objects are in thermal equilibrium.

9. What are the different methods of heat transfer?
   a. conduction, radiation, and reflection
   b. conduction, reflection, and convection
   c. convection, radiation, and reflection
   d. conduction, radiation, and convection

10. True or false—Conduction and convection cannot happen simultaneously
   a. True
   b. False

11.3 Phase Change and Latent Heat

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Explain changes in heat during changes of state, and describe latent heats of fusion and vaporization
- Solve problems involving thermal energy changes when heating and cooling substances with phase changes

Section Key Terms

condensation	freezing	latent heat	sublimation
latent heat of fusion	latent heat of vaporization	melting	vaporization
phase change	phase diagram	plasma	