11.2 Heat

To change the temperature, you usually need to add or subtract energy. For example, when it's cold outside, you turn up the *heat* in your house or apartment and the temperature goes up. You know that adding heat increases the temperature, but have you ever thought about exactly what "heat" is? What does "heat" have to do with temperature?

Heat, temperature, and thermal energy

What is heat? What happens when you hold a chocolate bar in your hand? Thermal energy flows from your hand to the chocolate and it begins to melt. We call this flow of thermal energy **heat**. Heat is really just another word for thermal energy that is moving. In the scientific sense, heat flows any time there is a difference in temperature. Heat flows naturally from the warmer object (higher energy) to the cooler one (lower energy). In the case of the melting chocolate bar, the thermal energy lost by your hand is equal to the thermal energy gained by the chocolate bar.

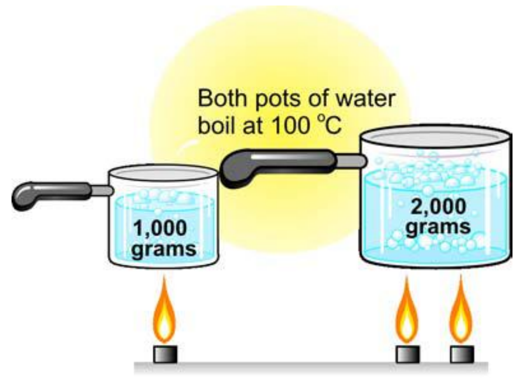


Figure 11.7: *It takes twice as much energy to heat a 2,000-gram mass of water compared to a 1,000-gram mass.*

Thermal energy depends on mass and temperature

Heat and temperature are related, but are not the same thing. The amount of thermal energy depends on the temperature but it also depends on the *amount* of matter you have. Think about heating up two pots of water. One pot contains 1,000 grams of water and the other contains 2,000 grams of water. Both pots are heated to the same final temperature (Figure 11.7). Which takes more energy? Or, do both require the same amount of energy? The pot holding 2,000 grams of water takes twice as much energy as the pot with 1,000 grams, even though both start and finish at the same temperature. The two pots illustrate the difference between temperature and thermal energy. The one with more mass has more energy, even though both are at the same temperature.

Units of heat and thermal energy

The joule The metric unit for measuring heat is the *joule*. This is the same joule used to measure all forms of energy, not just heat. A joule is a small amount of heat. The average hair dryer puts out 1,200 joules of heat every second!

The calorie

One *calorie* is the amount of energy (heat) needed to increase the temperature of 1 gram of water by 1 degree Celsius. One calorie is a little more than 4 joules (Figure 11.8). You may have noticed that most food packages list "Calories per serving." The unit used for measuring the energy content of the food we eat is the *kilocalorie*, which equals 1,000 calories. The kilocalorie is often written as Calorie (with a capital C). If a candy bar contains 210 Calories, it contains 210,000 calories, or 897,060 joules!

The British thermal unit

Still another unit of heat energy you may encounter is the *British thermal unit*, or Btu. The Btu is often used to measure the heat produced by heating systems or heat removed by air-conditioning systems. A Btu is the quantity of heat it takes to increase the temperature of 1 pound of water by 1 degree Fahrenheit. One Btu is a little more than 1,000 joules.

Why so many units?

The calorie and Btu units were being used to measure heat well before scientists knew that heat was really energy. The calorie and Btu are still used, even 100 years after heat was shown to be energy, because people give up familiar ways very slowly!

Specific heat

Temperature and mass

If you add heat to an object, how much will its temperature increase? It depends in part on the mass of the object. If you double the mass of the object, you need twice as much energy to get the same increase in temperature. The temperature increase also depends on what substance you are heating up. It takes different amounts of energy to raise the temperature of different materials.

Temperature and type of material

You need to add 4,184 joules of heat to one kilogram of water to raise the temperature by 1 °C. (Figure 11.9). You only need to add 470 joules to raise the temperature of a kilogram of steel by 1 °C. It takes 9 times more energy to raise the temperature of water by 1 °C than it does to raise the temperature of the same mass of steel by 1 °C.

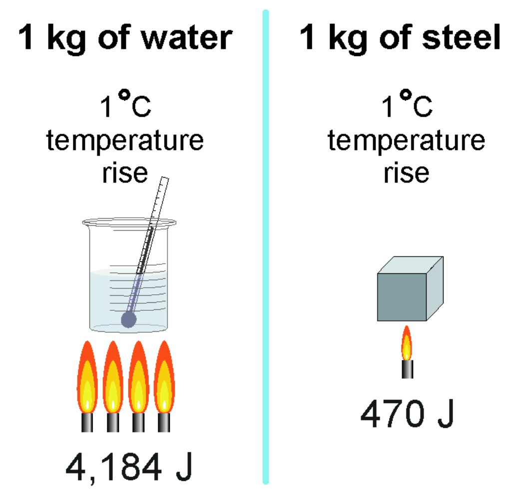


Figure 11.9: *Water and steel have different specific heats.*

Specific heat

Specific heat is a property of a substance that tells us how much heat is needed to raise the temperature of one kilogram by one degree Celsius. Specific heat is measured in joules per kilogram per degree Celsius (J/kg°C). A large specific heat means you have to put in a lot of energy for each degree increase in temperature.

Specific heat is the amount of energy that will raise the temperature of one kilogram of a substance by one degree Celsius.

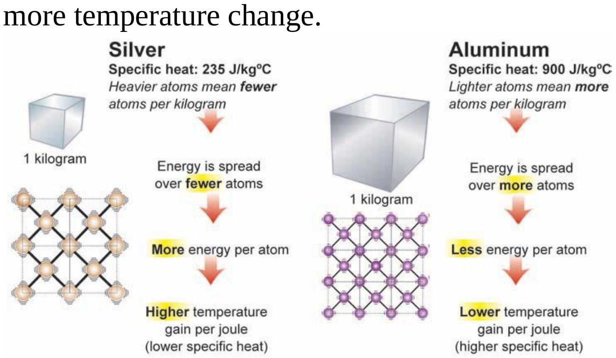
Uses for specific heat

Knowing the specific heat tells you how quickly the temperature of a material will change as it gains or loses energy. If the specific heat is *low* (like steel), then temperature will change relatively quickly because each degree of temperature change takes less energy. If the specific heat is *high* (like water), then the temperature will change relatively slowly because each degree of temperature change takes more energy. Hot apple pie filling stays hot for a long time because it is mostly water, and therefore has a large specific heat. Pie crust has a much lower specific heat and cools much more rapidly. The table in Figure 11.10 lists the specific heat for some common materials.

Why is specific heat different for different materials?

Why specific heat varies

In general, materials made up of heavy atoms or molecules have low specific heat compared with materials made up of lighter ones. This is because temperature measures the average kinetic energy *per particle*. Heavy particles mean fewer per kilogram. Energy that is divided between fewer particles means more energy per particle, and therefore more temperature change.



An example: silver and aluminum

Suppose you add 4 joules of energy to a kilogram of silver and 4 joules to a kilogram of aluminum. Silver's specific heat is 235 J/kg°C and 4 joules is enough to raise the temperature of the silver by 17 °C. Aluminum's specific heat is 900 J/kg°C. Four joules only raises the temperature of the aluminum by 4.4 °C. The silver has fewer atoms than the aluminum because silver atoms are heavier than aluminum atoms. When energy is added, each atom of silver gets more energy than each atom of aluminum because there are fewer silver atoms in a kilogram. Because the energy per atom is greater, the temperature increase in the silver is also greater.

Heat Transfer

The three ways heat flows

Thermal energy flows from higher temperature to lower temperature. This process is called *heat transfer*. How is heat transferred from material to material, or from place to place? It turns out there are three ways heat flows; *conduction*, *convection*, and *radiation*.

What is conduction?

Heat conduction is the transfer of heat by the direct contact of particles of matter. If you have ever held a warm mug of hot cocoa, you have experienced conduction. Heat is transferred from the mug to your hand. Conduction only occurs between two materials at different temperatures and when they are touching each other. In conduction, heat can also be transferred *through* materials. If you stir hot cocoa with a metal spoon, heat is transferred *from* the cocoa, *through* the spoon, and *to* your hand.

Conduction is the transfer of heat by the direct contact of particles of matter.

How does conduction work?

Imagine placing a cold spoon into a mug of hot cocoa (Figure 11.11). The molecules in the cocoa have a higher average kinetic energy than those of the spoon. The molecules in the spoon exchange energy with the molecules in the cocoa through collisions. The molecules within the spoon itself spread the energy up the stem of the spoon through the intermolecular forces between them. Heat conduction works both through collisions and also through intermolecular forces between molecules.

Figure 11.11: *Heat flows by conduction from the hot cocoa into, and up, the spoon.*

Thermal equilibrium

As collisions continue, the molecules of the hotter material (the cocoa) lose energy and the molecules of the cooler material (the spoon) gain energy. The kinetic energy of the hotter material is transferred, one collision at a time, to the cooler material. Eventually, both materials are at the same temperature. When this happens, they are in **thermal equilibrium**. Thermal equilibrium occurs when two bodies have the same temperature. No heat flows in thermal equilibrium because the temperatures are the same.

Thermal conductors and insulators

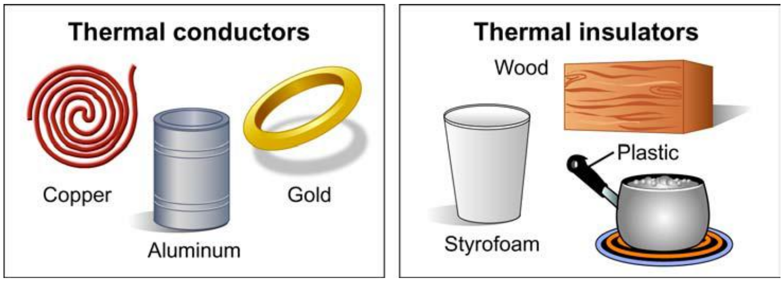
Which state of matter conducts best?

Conduction can happen in solids, liquids, and gases. Solids make the best conductors because their particles are packed closely together. Because the particles in a gas are spread so far apart, relatively few collisions occur, making air a poor conductor of heat. This explains why many materials used to keep things warm, such as fiberglass insulation and down jackets, contain air pockets (Figure 11.12).

Figure 11.12: *Because air is a poor conductor of heat, a down jacket keeps you warm in the cold of winter.*

Thermal conductors and insulators

Materials that conduct heat easily are called *thermal conductors* and those that conduct heat poorly are called *thermal insulators*. For example, metal is a thermal conductor, and a foam cup is a thermal insulator. The words *conductor* and *insulator* are also used to describe a material's ability to conduct electrical current. In general, good electrical conductors like silver, copper, gold, and aluminum are also good thermal conductors.



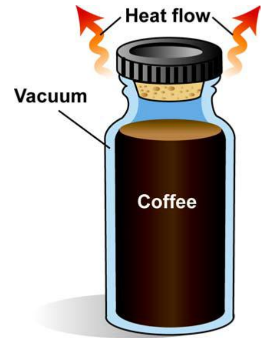


Figure 11.13: *A thermos bottle uses a vacuum to prevent heat transfer by conduction and convection*

Heat conduction cannot occur through a vacuum

Conduction happens only if there are particles available to collide with one another. Conduction does not occur in the vacuum of space. One way to create an excellent thermal insulator on Earth is to make a *vacuum*. A vacuum is empty of everything, including air. A thermos bottle keeps liquids hot for hours using a vacuum. A thermos is a container consisting of a bottle surrounded by a slightly larger bottle. Air molecules have been removed from the space between the bottles to create a vacuum (Figure 11.13).

Convection

What is convection?

Have you ever watched water boil in a pot? Bubbles form on the bottom and rise to the top. Hot water near the bottom of the pan circulates up, forcing cooler water near the surface to sink. This circulation carries heat through the water (Figure 11.14). This heat transfer process is called **convection.** Convection is the transfer of heat through the motion of matter such as air and water.

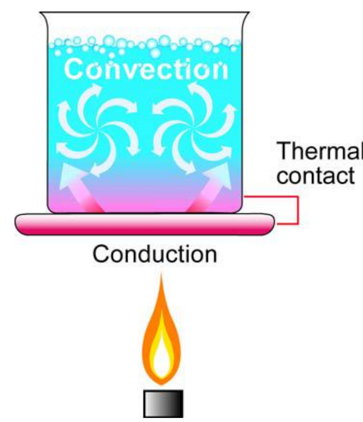


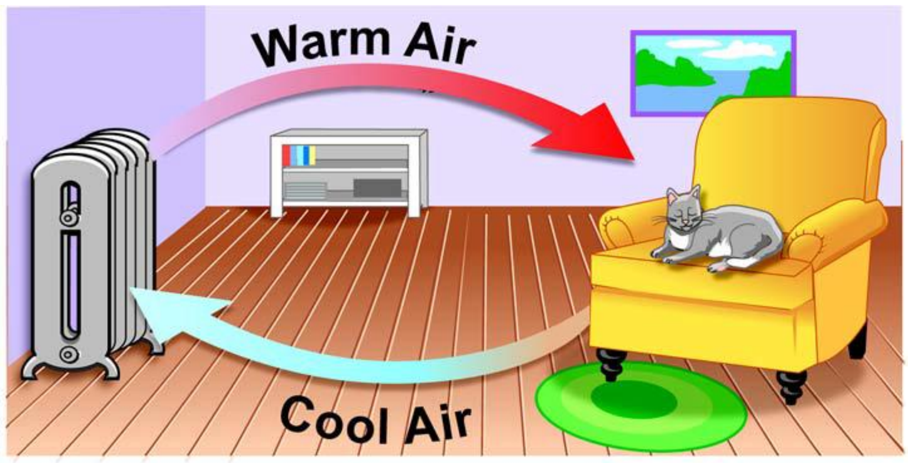
Figure 11.14: *Convection currents in water. The hot water at the bottom of the pot rises to the top and replaces the cold water*

Natural convection

Fluids expand when they heat up. Since expansion increases the volume, but not the mass, a warm fluid has a lower mass-to-volume ratio (called *density*) than the surrounding cooler fluid. In a container, warmer fluid floats to the top and cooler fluid sinks to the bottom. This is called *natural convection*.

Forced convection

In many houses a boiler heats water and then pumps circulate the water to rooms. Since the heat is being carried by a moving fluid, this is another example of convection. However, since the fluid is *forced* to flow by the pumps, this is called *forced convection*. Both natural and forced convection often occur at the same time. Forced convection transfers heat to a hot radiator. The heat from the hot radiator then warms the room air by natural convection. Convection is mainly what distributes heat throughout the room.



Thermal radiation

Definition of thermal radiation

If you stand in a sunny area on a cold, calm day, you will feel warmth from the Sun. Heat from the Sun is transferred to Earth by thermal radiation. **Thermal radiation** is electromagnetic waves (including light) produced by objects because of their temperature. All objects with a temperature above absolute zero (–273 °C or –459 °F) emit thermal radiation. To *emit* means to give off.

Thermal radiation is heat transfer by electromagnetic waves, including light.

Thermal radiation comes from atoms

Thermal radiation comes from the thermal energy of atoms. The power in thermal radiation increases with higher temperatures because the thermal energy of atoms increases with temperature (Figure 11.15). Because the Sun is extremely hot, its atoms emit lots of thermal radiation. Unlike conduction or convection, thermal radiation can travel through the vacuum of space. *All the energy the Earth receives from the Sun comes from thermal radiation.*

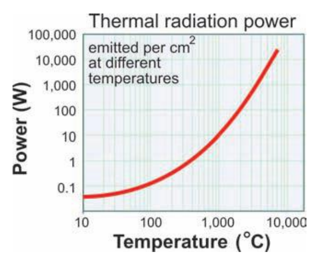


Figure 11.15: *The higher the temperature of an object, the more thermal radiation it emits.*

Objects emit and absorb radiation

Thermal radiation is also *absorbed* by objects. An object constantly receives thermal radiation from everything else in its environment. Otherwise all objects would eventually cool down to absolute zero by radiating their energy away. The temperature of an object rises if more radiation is absorbed. The temperature falls if more radiation is emitted. The temperature adjusts until there is a balance between radiation absorbed and radiation emitted.

Some surfaces absorb more energy than others

The amount of thermal radiation absorbed depends on the surface of a material. Black surfaces absorb almost all the thermal radiation that falls on them. For example, black asphalt pavement gets very hot in the summer Sun because it effectively absorbs thermal radiation. A silver mirror surface reflects most thermal radiation, absorbing very little (Figure 11.16). You may have seen someone put a silver screen across their windshield after parking their car on a sunny day. This silver screen can reflect the Sun's heat back out the car window, helping the parked car stay cooler on a hot day.

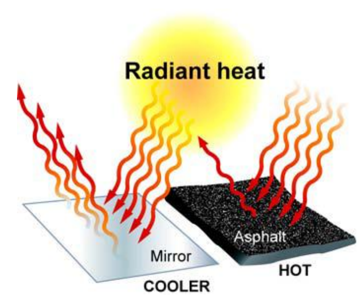
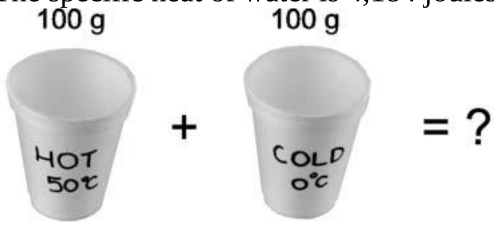


Figure 11.16: *Dark surfaces absorb most of the thermal radiation they receive. Silver or mirrored surfaces*

11.2 Section Review

1. What is the difference between temperature and heat?

2. Relative to 0 °C, the amount of thermal energy in a quantity of water is its mass × temperature × specific heat. The specific heat of water is 4,184 joules per kilogram per degree Celsius.



a. How much thermal energy is in 100 grams of water at 50°C?
b. How much thermal energy is in 100 grams of water at 0°C?
c. How much energy is there when both quantities of water are mixed together?
d. How much mass is this energy spread out over (in the mixture)?
e. What do you think the temperature of the mixture should be?

3. What conditions are necessary for heat to flow?

4. How much heat energy is required to raise the temperature of 20 kilograms of water from 0 oC to 35 oC?

5. What is thermal equilibrium?

6. How does heat from the Sun get to Earth?
a. conduction
b. convection
c. radiation

7. A down jacket keeps your body warm mostly by stopping which two forms of heat transfer? (Pick two.)
a. conduction
b. convection
c. radiation

Solving heat and temperature problems

How much heat does it take to raise the temperature of 5 kg of steel by 100 °C?
1. Looking for:
Amount of heat (energy)
2. Given:
Mass, and material (steel)
3. Relationships:
Relative to 0 °C, energy equals
mass × temperature × specific heat
4. Solution:
energy = (5kg) × (100 °C) × (470 J/kg°C)
= 235,000 joules

Your turn...

a. How much heat does it take to warm 1 kg of water by 10 °C? **Answer**:
41,840J