DU 7. HEAT AND TEMPERATURE

1. THERMAL ENERGY

Figure 7.

This unusual landscape is found in the hottest place in the U.S.A, in Death Valley, California. The air temperature near the ground can be as high as 57°C, and that is in the shade, (if you can find any)!
The sand's temperature in the baking sun can be much higher. If you were to walk barefoot on the hot sand, you would burn your feet. The air and sand in Death Valley have a lot of thermal energy.

What Is Thermal Energy?

Why does the air and sand in Death Valley feel so hot? It is because their particles are moving very rapidly. Anything that is moving has kinetic energy, and the faster it is moving, the more kinetic energy it has. The total kinetic energy of moving particles of matter is called **thermal energy**. It is not just hot things such as the air and sand of Death Valley that have thermal energy. All matter has thermal energy, even matter that feels cold. That is because all the matter particles are in constant motion and have kinetic energy.

Thermal Energy, Temperature, and Mass

Thermal energy and temperature are closely related. Both reflect the kinetic energy of moving particles of matter.

- ✓ T**emperature** is **the *average* kinetic energy of particles of matter**.
- ✓ T**hermal energy** is the ***total* kinetic energy of particles of matter.**

Does this mean that matter at a lower temperature has less thermal energy than matter at a higher temperature? Not necessarily. Another factor also affects thermal energy. The other factor is **mass**.

Q: Look at the pot of soup and the tub of water in the figure below. Which do you think has greater thermal energy?
A: The soup is boiling hot and has a temperature of 100°C, whereas the water in the tub is just comfortably warm, with a temperature of about 38°C. Although the water in the tub has a much lower temperature, it has greater thermal energy.

Figure 7.2

The particles in soup have greater average kinetic energy than the particles in water in a tub. This explains why soup has a higher temperature. However, the mass of the water in the tub is much greater than the soup's mass in the pot. This means that there are many more water particles than soup particles. All those moving particles give the water in the tub greater total kinetic energy, even though their average kinetic energy is less. Therefore, the water in the tub has greater thermal energy than the soup.

Q: Could a block of ice have more thermal energy than a pot of boiling water?

A: Yes, the block of ice could have more thermal energy if its mass were much greater than the mass of the boiling water.

Summary

- The **total kinetic energy** of moving particles of matter is called **thermal energy**.
- The **thermal energy of matter depends on how fast its particles are moving on average**, which is measured by **temperature**, and also on **how many particles there are**, which is measured by **mass**

2. TEMPERATURE AND TEMPERATURE SCALES

This girl has a fever, and it makes her feel really tired. She also feels hot because her temperature is higher than normal. She has a **thermometer** in her mouth to measure her **temperature**.

Figure 7.3

What Is Temperature?

No doubt you already have a good idea of what temperature is.

You might say that it is how warm or cool something feels.

In physics, **temperature** is defined as **the average kinetic energy of the particles of matter**.

- ✓ When particles of matter move faster, they have **more kinetic energy**, so their **temperature is higher**. **With a higher temperature, matter feels warmer**.
- ✓ When particles move more slowly, they have **less kinetic energy on average**, so their **temperature is lower**. **With a lower temperature, matter feels cooler**.

Measuring temperature

A **thermometer** is the device that measures temperature.

Many thermometers measure temperature with a liquid that **expands** when it gets warmer and **contracts** when it gets cooler.

Look at the common thermometer pictured in the figure below. The red liquid rises or falls in the glass tube as the temperature changes. Temperature is read on the scale at the liquid's highest point in the tube.

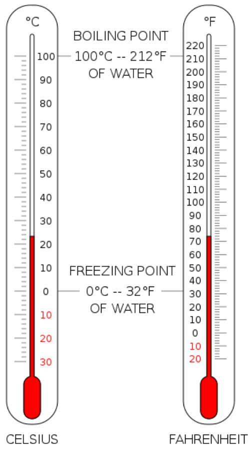


Figure 7.4

The red liquid in the thermometer is **alcohol**. Alcohol expands uniformly over a wide range of temperatures. This makes it ideal for use in thermometers.

Q: Why does the liquid in the thermometer expand and contract when the temperature changes?

A: When the temperature is higher, the liquid's particles have greater kinetic energy, so they move about more and spread apart. This causes the liquid to expand. The opposite happens when the temperature is lower, and the liquid's particles have less kinetic energy. The particles move less and crowd closer together, causing the liquid to contract.

Temperature Scales

The thermometer pictured in the f**igure** above measures temperature on two different **scales**: **Celsius** (C) and **Fahrenheit** (F).

Although some scientists use the Celsius scale, **the SI scale for measuring temperature is the Kelvin scale**. Those who live in the U.S.A are probably most familiar with the Fahrenheit scale.

Thermometers are used to measure temperature according to well-defined scales of measurement, which use reference points to help compare quantities. A temperature scale can be created by **identifying two easily reproducible temperatures**. The **freezing** and **boiling temperatures of water** are commonly used.

- **The centigrade scale or Celsius scale**

Anders Celsius originally devised this scale in 1742 and was a Swedish physicist and astronomer. The Celsius scale has the freezing point of water at 0ºC, and the boiling point at 100ºC. Its unit is the **degree Celsius ºC.**

- **The absolute scale or Kelvin scale**

The **Kelvin** scale is the temperature scale that is commonly used in science. It is an *absolute temperature* scale defined to have 0 K at the lowest possible temperature, called **absolute zero**.

What is absolute zero? Absolute zero is the temperature at which **all molecular motion has ceased.** There cannot be a lower temperature because the temperature measures the movement of particles.

The official temperature unit on this scale is the **kelvin**, which is abbreviated **K**, and is **not accompanied by a degree sign.**

The **freezing and boiling points of water are 273.15 K and 373.15 K**, respectively. Thus, the magnitude of temperature differences is the same in units of kelvins and degrees Celsius.

Unlike other temperature scales, the Kelvin scale is an **absolute scale**. **The kelvin is the SI unit used in scientific work.**

The image below compares all three temperature scales. Each scale uses the freezing and boiling points of water as reference points. Notice that temperatures on the Kelvin scale are not given in degrees (°).

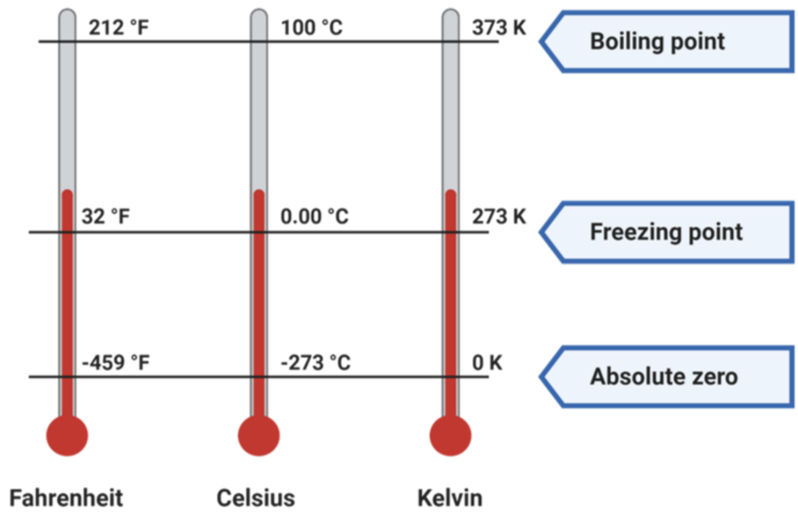


Figure 7.5

Because the Celsius and Kelvin temperature scale is frequently used, it is useful to know how to convert temperatures from one scale to another. It is easy to convert temperatures between the Kelvin and Celsius scales.

Each 1-degree change on the Kelvin scale is equal to a 1-degree change on the Celsius scale.

Therefore, to convert a temperature **from Celsius to Kelvin, just add 273 to the Celsius temperature.** For example, 10°C equals 283 Kelvin.

Summary

- Temperature is the average kinetic energy of particles of matter.
- A thermometer can measure temperature with a liquid that expands when it gets warmer and contracts when it gets cooler
- The SI scale for measuring temperature is the Kelvin scale. Celsius and Fahrenheit temperature scales are also commonly used.

3. THERMAL EXPANSION OF SOLIDS, LIQUIDS AND GASES

Figure 7.6

Thermal expansion joints like these on a bridge allow bridges to change length without buckling.

The expansion of alcohol in a thermometer is one of many commonly encountered examples of **thermal expansion**, **the change in size or volume of a given mass with temperature**.

Hot air rises because its volume increases, which causes the hot air's density to be smaller than the density of surrounding air, causing a buoyant (upward) force on the hot air.

The same happens in all liquids and gases, driving **natural heat transfer upwards in homes**, **oceans**, **and weather systems**.

Solids also undergo thermal expansion. Railroad tracks and bridges, for example, have expansion joints to allow them to freely expand and contract with temperature changes.

As we have seen in Kinetic Theory of matter, **an increase in temperature implies an increase in the kinetic energy** of the individual atoms and particles, and, therefore, they move faster. Hence, **the distances between the particles get bigger**, and they take up more space. The result is that the body increases its volume, it **expands**.

Expansion in solids and liquids

In a **solid or a liquid**, unlike in a gas, the atoms or molecules are closely packed together, but their kinetic energy (in the form of small, rapid vibrations in solids, also transfers in liquids) pushes neighbouring atoms or molecules apart from each other. This neighbour-to-neighbour pushing results in a slightly greater distance, on average, between neighbours.

For most substances under ordinary conditions, there is no preferred direction, and an increase in temperature will increase the body´s size by a certain fraction in each dimension.

Not all substances expand in the same way, some expand more than others. The change in length **L** is proportional to length **L**. The dependence of thermal expansion on temperature, substance, and length is summarized in the equation:

$$\boxed{L = L_0 (1 + \alpha \times \Delta T)}$$

L= length of the bar

L_0= initial length before heating

ΔT = the variation in temperature

α (alpha) = the coefficient of linear expansion (different value for different substances)

Material	Coefficient of linear expansion $\alpha\,(1/C)$
Solids	
Aluminum	2510^{-6}
Brass	1910^{-6}
Copper	1710^{-6}
Gold	1410^{-6}
Iron or Steel	1210^{-6}
Invar (Nickel-iron alloy)	0.910^{-6}
Lead	2910^{-6}
Silver	1810^{-6}
Glass (ordinary)	910^{-6}
Glass (Pyrex®)	310^{-6}
Quartz	0.410^{-6}
Concrete, Brick	1210^{-6}

The table shows the **coefficient values of linear expansion for different substances**, which may have units of 1/°C or 1/K.

Expansion of gases. Charles Law

Although solids and liquids expand very slightly when they heat up, gases expand greatly when the temperature rises.

Remember that in gases, particles are far apart, have complete freedom of movement, and their kinetic energy is high. Because of these, in the case of gases, it is more appropriate to talk about an increase in volume than an increase in length.

Perhaps you might have observed that after you inflate a pool inflatable and push it into the pool, it seems a bit under-inflated. This is not because of any leak in the float, this happens because **the water temperature in the pool is low, which reduces the volume of the air inside.**

Figure 7.7

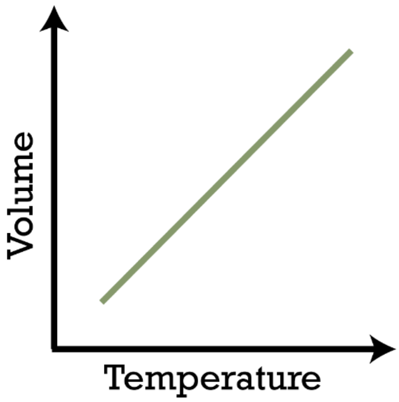
Charles's Law

Charles's Law was discovered in the 1700s by a French physicist named Jacques Charles.

According to **Charles's Law**, **if the pressure of a gas is held constant, increasing the temperature of the gas increases its volume.**

What happens when a gas is heated? Its particles gain energy. As more energy is gained, the particles react at a greater speed. Therefore, they can move more and spread out farther. The volume of the gas increases as it expands and takes up more space.

The graph in the figure below shows this relationship between the temperature and volume of a gas.



As the temperature of a gas increases, its volume also increases.

Charles´s Law expressed mathematically:

$$\boxed{V = k \times T}$$

k= proportionally constant between volume and temperature

Another way of expressing this law is:

$$\boxed{\frac{V}{T} = \text{constant} = k}$$

This means that the ratio between the volume of a gas and its temperature is constant

So, if a gas occupies a volume V_1 at an absolute temperature T_1, and at another temperature T_2 would occupy a volume V_2, the relationship between all these magnitudes is:

$$\boxed{\frac{V_1}{T_1} = \frac{V_2}{T_2}}$$

Summary:

- All substances expand when their temperature rises.
- Expansion is small in solids and liquids, but large in gases.
- Charles´s Law describes the expansion of a gas.

4. THERMAL EQUILIBRIUM

Watch out! This chef is taking food out of a hot oven using an oven mitt. Touching the baking pan with bare hands could cause a painful burn. However, the air inside the oven does not hurt. How can this be? Explore the Hot Oven simulation below to find out:

What Is Heat?

Heat is the transfer of thermal energy between substances.

Thermal energy is the kinetic energy of moving matter particles, measured by their temperature. **Thermal energy always moves from warmer to cooler substances.** You can see this in the figure below.

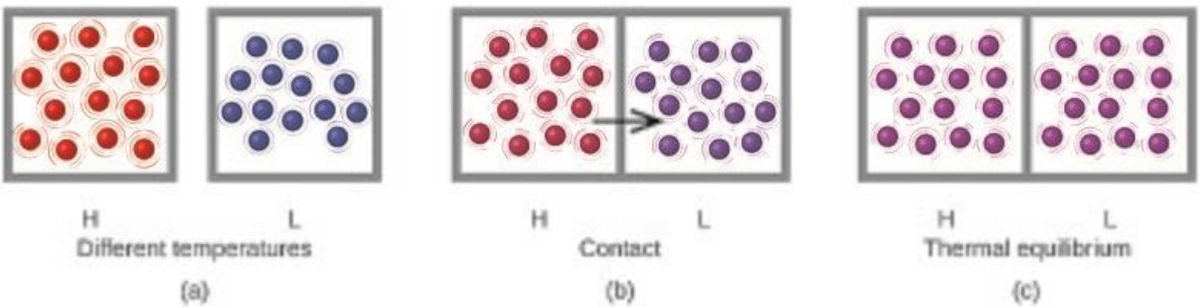


Figure 7.8

(a) Substances H and L are initially at different temperatures, and their atoms have different average kinetic energies. (b) When they come into contact with each other, collisions between the molecules result in the transfer of kinetic (thermal) energy from the hotter to the cooler matter. (c) The two objects reach "thermal equilibrium" when both substances are at the same temperature, and their molecules have the same average kinetic energy.

Faster-moving particles of the warmer substance bump into and transfer some of their energy to slower-moving particles of the cooler substance.

Thermal energy is transferred in this way until both substances have the same thermal energy and temperature. The transfer of energy stops when both bodies and systems reach the same temperature.

Q: How is thermal energy transferred in an oven?

A: Thermal energy of the hot oven is transferred to the cooler food, raising its temperature.

Cooling Down by Heating Up

How do you chill a glass of room-temperature cola? You would probably add ice cubes to it, as in the figure below. You might think that the ice cools down the cola, but in fact, it works the other way around. **The warm cola heats up the ice**.

Thermal energy from the warm cola is transferred to the much colder ice, causing it to melt.

Figure 7.9

The cola loses thermal energy in the process, so its temperature falls.

Summary

- Heat is the transfer of thermal energy between substances. Thermal energy is the kinetic energy of moving particles of matter, measured by their temperature.
- Thermal energy always moves from warmer to cooler substances until both substances have the same temperature.

Measuring Heat

Heat is energy that is transferred between objects at different temperatures, so, heat has the same units of measurement as energy. **The SI unit of heat is the joule, J.**

Nevertheless**, the traditional unit for measuring heat is the calorie, cal.**

This unit is commonly used on dietary and nutritional information labels for food.

A calorie is defined as the amount of heat to heat 1 gram of water by one degree.

The equivalent between cal and J: **1cal = 4,18 J**

5. SPECIFIC HEAT

If it Is a warm, sunny day on the beach in the summertime, the sand feels hot on our bare feet. We take a dip in the water, if we want to cool off, because the water feels much cooler than the sand.

Why does the sand—but not the water—get hot in the sun? The answer has to do with specific heat.

Specific heat is a measure of how much energy it takes to raise the temperature of a substance. **It is the amount of energy (in joules) needed to raise the temperature of 1 gram of the substance by 1 °C.**

Specific heat is a property that is **specific to a given type of matter**. That's why it's called *specific*.

Metals such as iron have **low specific heat**. It does not take much energy to raise their temperature. That is why a metal spoon heats up quickly when placed in a cup of hot coffee.

Sand also has a relatively low specific heat.

Water, on the other hand, has a **very high specific heat**. **It takes a lot more energy to increase the temperature of water than it does sand.** This explains why the sand on a beach gets hot while the water stays cool. **Differences in the specific heat of water and land even affect climate.**

Q: Metal cooking pots and pans often have wooden handles. Can you explain why?

A: Wood has a higher specific heat than metal, so it takes more energy to heat a wooden handle than a metal handle. As a result, a wooden handle would heat up more slowly and be less likely to burn your hand when you touch it.

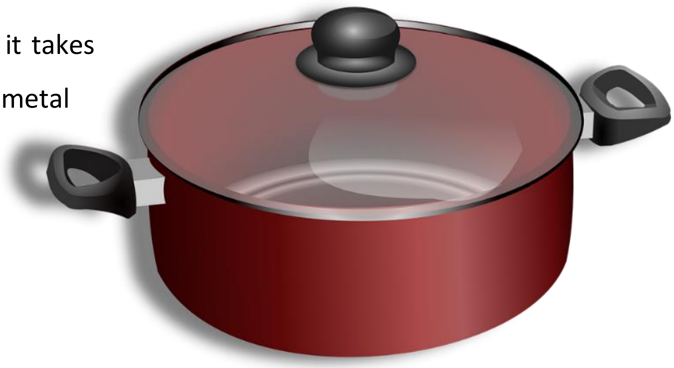


Figure 7.10

Summary

- Specific heat is a measure of how much energy it takes to raise a substance's temperature. It is the amount of energy (in joules) needed to raise the temperature of 1 gram of the substance by 1°C.
- Specific heat is a property that is specific to a given type of matter, and substances vary in their specific heat. Metals tend to have low specific heat. Water has extremely high specific heat.

6. HEAT TRANSFER

Heat can be transferred from one body to another in three diverse ways: conduction, convection, and radiation.

CONDUCTION

Conduction is the **transfer of thermal energy between particles of matter that are touching**.

Thermal energy is the total kinetic energy of moving particles of matter, and the transfer of thermal energy is called **heat**.

Conduction is one of three ways that thermal energy can be transferred (the other ways are convection and thermal radiation). Thermal energy is always transferred from matter at a higher temperature to matter at a lower temperature.

How conduction works

To understand **how conduction works**, you need to think about the **tiny particles** that make up matter. The particles of all matter are in constant random motion, but the particles of warmer matter have more energy and move more quickly than the particles of cooler matter.

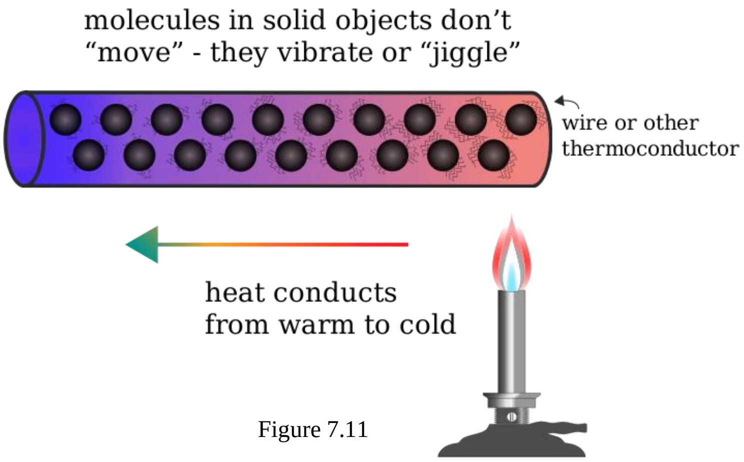


Figure 7.11

An illustration of heat transfer through conduction.

When particles of warmer matter collide with particles of cooler matter, **they transfer some of their thermal energy to the cooler particles**. From particle to particle, like dominoes falling, thermal energy moves through matter.

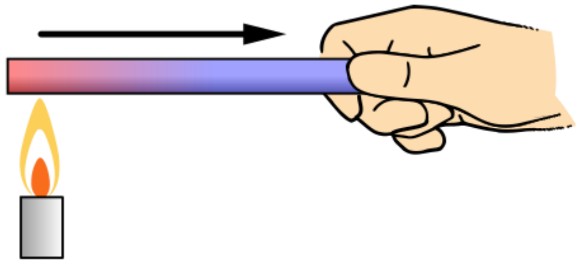


Figure 7.12

Example of heat conduction. The arrow shows the direction of heat flow in the rod.

Figure 7.13

Example of heat conduction. A hot iron removes the wrinkles in a shirt.

Thermal Conductors and Isolators.

The **thermal conductivity** of a substance is a measure of the substance's ability to conduct heat. We can distinguish between thermal conductors and thermal isolators

- **Thermal conductors**: materials with a high thermal conductivity can effectively transfer heat and readily soak up heat from their environment. They quickly transfer thermal energy from one point to another.

  Examples: metals (silver, aluminum, copper)

- **Thermal isolators**: materials with a low thermal conductivity, which transfer thermal energy slowly from one point to another. They resist heat flow and slowly obtain heat from their surroundings.

  Examples: wood, cork.

CONVECTION

Can you see the water bubbling in this pot? The water is boiling hot.

How does all the water in the pot get hot when it is heated only from the bottom by a gas flame? The answer is **convection.**

Convection is the transfer of thermal energy by particles moving through a fluid (either a gas or a liquid).

Figure 7.14

Thermal energy is the total kinetic energy of moving particles of matter, and the transfer of thermal energy is called heat.

Convection is one of three ways that thermal energy can be transferred (the other ways are conduction and thermal radiation). Thermal energy is always transferred from matter with a higher temperature to matter with a lower temperature.

How Does Convection Occur?

The figure below shows how convection occurs, using hot water in a pot as an example.

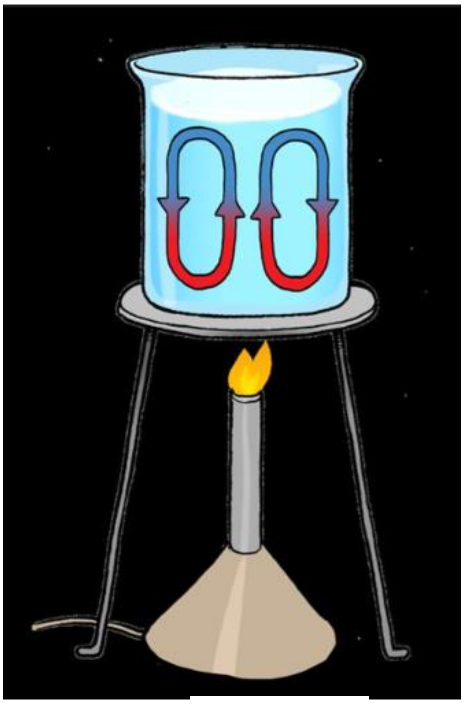


Figure 7.15

When particles in one area of a fluid (in this case, the water at the bottom of the pot) gain thermal energy, they move more quickly, collide more, and spread farther apart. This **decreases the density of the particles**, so **they rise through the fluid**.

As they rise, they transfer their thermal energy to other particles in the fluid and cool off in the process.

With less energy, the particles move more slowly, have fewer collisions, and move closer together. This increases their density, so they **sink back down through the fluid**. When they reach the bottom of the fluid, **the cycle repeats**. The result is a loop of moving particles called a **convection current**.

Examples of Convection

Convection currents transfer thermal energy through many fluids, not just hot water in a pot. For example, convection currents transfer thermal energy **through molten rock below the Earth's surface, through water in the oceans, and through air in the atmosphere.**

Convection currents in the atmosphere create **winds**. You can see one way this happens in the figure below. The land heats up and cools off faster than the water because it has lower specific heat. Therefore, the land gets warmer during the day and cooler at night than the water does. During the day, warm air rises above the land and cool air from the water moves in to take its place. During the night, the opposite happens. Warm air rises above the water and cool air from the land moves out to take its place.

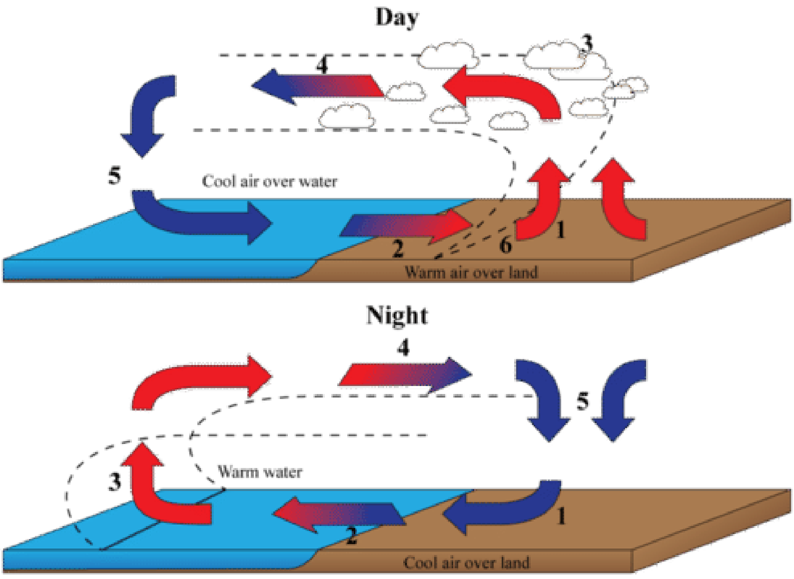


Figure 7.16

Q: During the day, in which direction is thermal energy of the air transferred? In which direction is it transferred during the night?

A: During the day, thermal energy is transferred from the air over the land to the air over the water. During the night, thermal energy is transferred in the opposite direction.

Thermal Radiation

Figure 7.17

Someone is warming their hands over a bonfire. They do not have to touch the fire to feel its warmth. How is warmth from the fire transferred to their hands?

The bonfire from the opening image has a lot of thermal energy.

Thermal energy from the bonfire is transferred to the hands by thermal radiation.

Thermal radiation is the **transfer of thermal energy by waves travelling through the air or even through empty space**, as shown in the figure below. When the waves of thermal energy reach objects, they transfer the energy to the objects, causing them to warm up. This is how the fire warms the hands of someone sitting near the bonfire.

This is also how the Sun's energy reaches the Earth and heats its surface. Without the energy radiated from the Sun, the Earth would be too cold to support life as we know it.

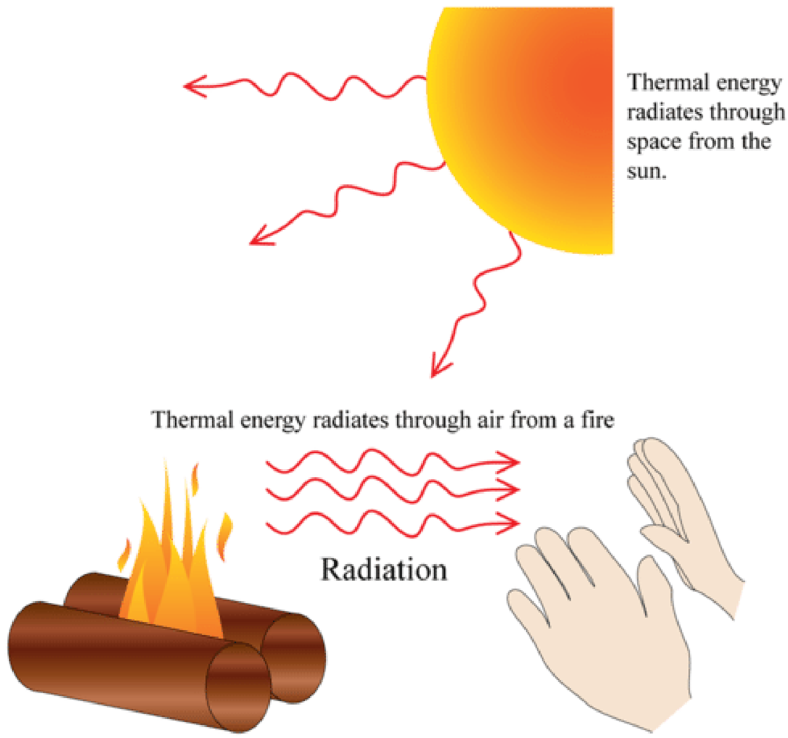


Figure 7.18

Everything radiates thermal energy, not just really hot things such as the sun or a fire.

For example, when it's cold outside, a heated home radiates some of its thermal energy into the outdoor environment.

Even people radiate thermal energy. In fact, when a room is full of people, it may feel noticeably warmer because of all the thermal energy people radiate!

Summary

- Heat is transferred by **conduction**, **convection**, and **radiation**.
- **Conduction** is the transfer of thermal energy between particles of matter that are touching. Thermal energy is always transferred from particles of warmer matter to particles of cooler matter.

- When particles of warmer matter collide with particles of cooler matter, they transfer some of their thermal energy to the cooler particles.
- **Convection** is the transfer of thermal energy by particles moving through a fluid. Thermal energy is always transferred from an area with a higher temperature to an area with a lower temperature.
- Moving particles transfer thermal energy through a fluid by forming convection currents.
- Convection currents move thermal energy through many fluids, including molten rock inside the Earth, water in the oceans, and air in the atmosphere.
- **Thermal radiation** is the transfer of thermal energy through waves that can travel through air or even through empty space. This is how thermal energy from a fire is transferred to your hands and how thermal energy from the Sun is transferred to the Earth.
- Everything radiates thermal energy, even objects that are not very warm.

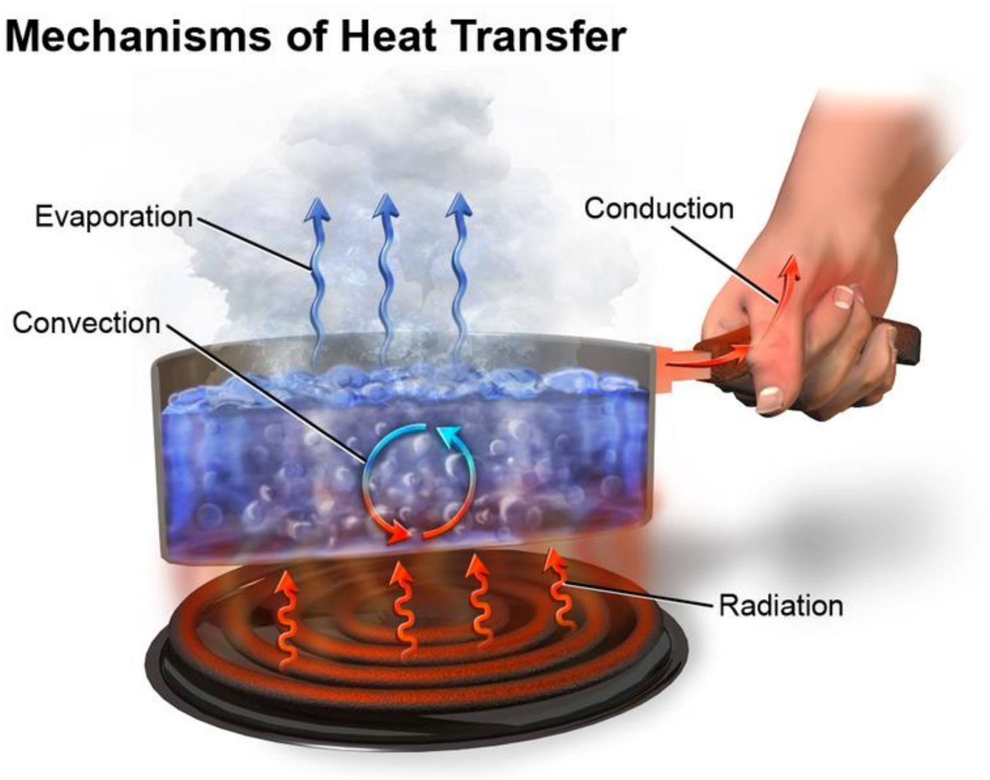


Figure 7.19

7. ENERGY EFFICIENCY

Energy efficiency simply means using less energy to perform the same task – that is, **eliminating energy waste.**

Energy efficiency brings a variety of benefits as it reduces greenhouse gas emissions, reduces the demand for energy imports, and lowers costs on a household and an economy-wide level.

If we focus on thermal efficiency, if we know how the processes of transferring heat occurs, we can save energy and increase the efficiency of transferring the heat we want for heating or cooling buildings, for example.

The transfer of heat by conduction has special importance in this aspect. Heat transfer obeys **Newton´s Law of Cooling**.

> The rate of heat exchange between an object and its surroundings is proportional to the difference in temperature between the object and the surroundings.

Q: If we think of a room with thick walls that separate it from the outside, what does the speed at which heat is transferred through the walls by thermal conduction depend on?

A: It depends on different factors: the difference between the temperature on either side of the wall, the wall size, the thermal conductivity of the materials used to make the walls and the thickness of the wall.

Taking all these into consideration, it can be deduced that, in order to reduce heat loss in homes, we have to insulate the walls efficiently, and seal draughts around windows and doors, a major source of heat loss in homes.

Summary

- We can save energy by knowing about the processes of heat transfer.
- It is possible to reduce heat loss at home by insulating the walls and sealing leaks around doors and windows.