Integrated Science V2

Science course from Educational Options

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Lesson 10: Heat and Temperature

Objectives

By the end of this lesson, students will be able to:

- define temperature, heat, and thermal energy
- distinguish between temperature, heat, and thermal energy
- identify three scales used to measure temperature
- convert temperature readings between Fahrenheit, Celsius, and Kelvin scales
- describe the three methods of heat transfer
- explain thermal expansion and contraction
- describe how the uses of heat impact our daily lives

Click here for the course glossary

Introduction

Contractors who remodel kitchens and bathrooms deal with extremely hard materials such as marble, granite, and concrete. If you have never seen a countertop installed, it is very labor intensive. The installation team spends hours drilling holes for fixtures and cutting openings to fit a sink. If you have seen a team like this at work, then you have also seen the tools that they use. They use special saws and drills with diamond drill bits. These drill bits are made with diamond because diamond is one of the hardest materials in nature, and it can cut through materials like granite without breaking easily.

A diamond-coated drill bit

Diamond-coated drill bits eventually wear out, and they are expensive to replace. Recent technology has enabled them to last longer by adding cooling systems to the drills. Running water through the drill or around the material being drilled keeps the drill bit cool so its sharp edge will last longer. It prevents heat from harming the bit or the materials.

This lesson focuses on heat and temperature. In this lesson you will learn more about why a cooling system is useful and necessary for drills and in other situations. You will learn the difference between heat and temperature, methods of heat transfer, and look at the many ways that heat impacts our daily lives.

What Is Temperature?

When you touch something, you know whether it is hot or cold. When you want to measure how hot or cold something is, you use a thermometer. **Temperature** is a measure of how hot or cold something is when it is compared to a **reference point**, a mark to which all other measurements can be compared.

Temperature is related to **kinetic energy** and the motion of an object's particles through space. When an object gets hotter, its particles move around faster. This creates more kinetic energy and raises the temperature.

Temperature Scales

What exactly is a reference point? Because people perceive hot and cold differently, standard reference points were created so that it would be universally understood. Different temperature scales have different reference points.

Two common types of temperature scales are Celsius and Fahrenheit.

There are several temperature scales in use today. The Celsius scale is used around the world for scientific research. Its reference points are 0° C for the freezing point of water and 100° C for the boiling point of water.

The Fahrenheit scale is used mostly in English speaking countries. It is based on the mercury thermometer and is not used for scientific research. On the Fahrenheit scale, the reference points are 32° F for the freezing point of water and 212° F for the boiling point of water.

The SI unit for measuring temperature is the Kelvin. The Kelvin scale is the most commonly used scale in the scientific community. The Kelvin scale is based on the concept of **absolute zero**, the lowest point of the temperature scale. Absolute zero is equal to -273.15° C or -459.67° F. At absolute zero, there is no motion of any particle, not even **electrons**.

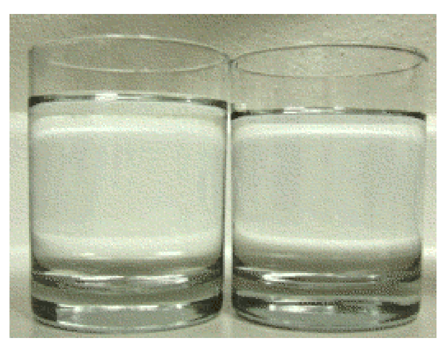
So far, absolute zero only exists in theory. The closest any team of scientists has come to measuring absolute zero is at the Helsinki University of Technology, where scientists cooled a piece of rhodium metal to 0.0000000001 K (or 100 pK). In the study of cryogenics, temperatures as low as 0.003 K have been produced. Another scale for measuring temperature that also uses absolute zero is the Rankine scale.

What Is Heat?

Before you learn about heat, here is how the diamond drill bit mentioned in the introduction works. The drill performs **work** on the granite countertop. Remember from the lesson on simple machines that no machine is perfectly efficient. During drilling some of the energy is lost to **friction**. Friction causes the moving parts to heat up, and they get even hotter as more work is done by the drill. Cooling systems are necessary to cool the machinery and keep too much heat from building up. Heat naturally flows from hotter to cooler objects. The heat that is generated by the drill flows to the cooler water instead of remaining in the drill or around the drill bit.

In this case, what we are calling heat is actually a form of energy called *thermal energy*. Remember that **thermal energy** is the total amount of kinetic energy and **potential energy** of all of the particles in an object. The amount of thermal energy given off depends on mass, temperature, and the phase of the object (whether the object is a solid, liquid, or gas). **Heat**, on the other hand, is the transfer of thermal energy from one object to another due to a difference in temperature.

Try This!



Look at the two containers filled with tea.

This cup of hot tea has a higher temperature than the glass of iced tea because its particles have a higher average kinetic energy.

This glass of iced tea has a lower temperature, but it has more thermal energy. This is because there are many more particles of tea inside the glass than there are in the cup of hot tea.

Heat and Energy
Molecules that are heated move faster than molecules that are cold. You can test this by comparing how quickly water disperses food coloring. Take two glasses and fill one with hot water and the other with cold water. Place the glasses side by side on a flat surface. Add two drops of food coloring to each glass. The glass of hot water will disperse the food coloring more quickly than the cold because the molecules of the hot water are moving faster. The animation above shows food coloring dispersing in a glass of cold water and a glass of hot water. Which glass do you think contains the hot water and which glass contains the cold water?

Heat flows from higher temperatures to lower temperatures. Imagine that the iced tea above was just brewed. While it was in the pitcher it was warm, and its particles were moving quickly. When the ice was added to the pitcher, more particles were introduced. Because they were cold, they did not move as quickly. As all of the particles bounced around, they collided with each other. When particles collide, they exchange energy. High energy particles lose energy and low energy particles gain energy. In this way, thermal energy is transferred from high temperatures to low temperatures. The particles in the pitcher will continue to collide and transfer energy until they all reach the same temperature.

Think About It

Does the ice in your drink release the cold into your drink or does it absorb the heat from your drink?

Contraction and Expansion

Have you ever wondered why sidewalks are put down in slabs of concrete, and not poured in one continuous line of concrete? The answer is expansion and contraction, properties of thermal energy. As you have already read, when an object is warm its particles move around quickly. The warmer it is, the faster the particles move. In some objects, this causes the object to swell slightly. You may experience this in the summer if you have wooden doors in your house. They "stick" in the summer because of the swelling. Remember that thermal energy depends on mass, temperature, and the phase of the object. **Thermal expansion** occurs when particles of matter move farther apart when the temperature increases.

When the weather is cold, the particles of objects move much more slowly. They do not collide as often and they do not exert as much force on each other. This keeps the object at its original size or in some cases even shrinks the object. For example, if you take a balloon outside on a cold day it will appear to lose air. The air is not lost; its particles are just moving more slowly, causing **thermal contraction**. The balloon is also an example of how the object's phase affects thermal energy. Gas expands more easily than liquid or solid.

There is one exception to the laws of expansion and contraction. Water between 0° C and 4° C contracts, even as it gets warmer. This is because ice is less dense than water. As water freezes, the bonded water molecules in ice arrange themselves in a way that takes up more space than they do in liquid water. When a pond freezes in the winter, the denser, warmer water is pushed to the bottom as the less dense, cooler ice floats on the top. This is how fish survive under a frozen pond.

Measuring Heat

Think back to when you were younger and went to the playground to play on a sunny day. The monkey bars and swings were fun, but if the day was hot and sunny, that metal slide was way too hot to go down! Why did the slide get hotter than the other equipment? The answer is specific heat. The metal slide has a lower specific heat than the molded plastic around the monkey bars or the seat of the swing. **Specific heat** is the amount of heat necessary to raise the temperature of one gram of a material by one degree Celsius. The lower a material's specific heat, the hotter it will get when its mass absorbs a given amount of heat. Equal masses of the slide and swing seat absorb the same amount of heat from the sun, but the slide's temperature rises more because its specific heat is lower. Less energy is needed to raise its temperature.

Specific heat is measured in joules per gram per degree Celsius, or J/g•°C. Look at the chart below, which lists the specific heat for a few common substances.

Specific Heats of Materials

Material	Specific Heat (J/g•°C)
Iron	0.45
Air	1.01
Wood	1.76
Olive Oil	2.00
Water	4.18

This table tells you that it takes 4.18 joules of energy to heat up 1 gram of water by 1 degree. However, it only takes 2 joules of energy to heat up 1 gram of olive oil by 1 degree. To heat 2 grams of olive oil, you would need 4 joules of energy. A high specific heat means the object resists being heated.

An electric calorimeter

A change in thermal energy is measured using a calorimeter, an instrument that measures the quantity of heat in a solution or chemical reaction. The design of the calorimeter is based on the principle that heat flows from hotter objects to cooler objects. To measure an object's specific heat, the object with a known mass is heated and placed in a sealed container of water (also with a known mass). The heated object cools off, and the water is stirred to distribute thermal energy evenly. The calorimeter then measures the change in the temperature of the water. The thermal heat that is in the water is calculated according to the specific heat equation:

Heat = Mass × Specific Heat × Change in Temperature

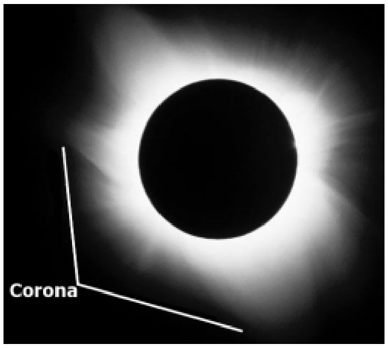
$$Q = m \times c \times \Delta T$$

In this formula, heat is in joules, mass is in grams, specific heat is in J/g•° C, and the temperature change is in degrees Celsius. The amount of thermal energy in the water will be the same amount given off by the heated object, so the specific heat of that object can be found. The unit for specific heat is the joule.

Note that this formula is not listed below in the Important Formulas to Remember section. You will not need to memorize it or use it to solve homework or submission problems. It is here only to help explain how a calorimeter determines how much thermal energy is given off by the water.

How Heat and Temperature Differ

Now you know that temperature depends on kinetic energy and the movement of particles in an object or substance. You also know that heat is a form of energy called thermal energy. Temperature and thermal energy are two very different things that often work together.



The corona is best seen during a solar eclipse; it appears as a white ring around the blocked-out sun in this picture.

The Sun's corona is an example of the difference between thermal energy and temperature. The corona is the atmosphere around the sun that extends many millions of kilometers into space. The corona is easiest to see during a solar eclipse, as in the picture.

To scientists who study solar physics, this part of the Sun is still a mystery. While the Sun's surface is extremely hot at more than 5800 K, the Sun's corona ranges between one and three million kelvin! The simple explanation for this phenomenon is this: the corona has only a few atoms that are moving quickly. The rapid movement means the temperature is high. However, since there are very few atoms (or particles if you think back to the tea example) that are moving, the thermal energy given off is very low. This is one of several theories that attempt to explain the characteristics of the Sun's corona, but scientists cannot explain exactly why the corona is hotter than the surface of the Sun.

How Do I Convert Temperature Measurements?

Occasionally you may need to convert a measurement from one temperature scale to another. Many different countries and circumstances require knowledge of different temperature scales. Look at the following situations where the individuals found the need to convert temperature readings.

Converting to Degrees Celsius to Degrees Fahrenheit

Loren is an exchange student who is packing for his trip home to England for the holidays. He turns on the cable weather channel to see what the weather will be like in London when he gets home. He sees that for the next few weeks the average temperature will be about 52° F. At first Loren is amazed! Fifty-two degrees is extremely hot! Then he realizes that Americans use Fahrenheit as the unit for measuring weather. Loren has to convert 52° F to degrees Celsius to find out what to expect from the weather at home:

$$\textbf{Celsius} = \frac{5}{9} \times (°\,\textbf{Fahrenheit} - 32)$$

$$\text{Celsius} = \frac{5}{9} \times (52° - 32)$$

$$\text{Celsius} = \frac{5}{9} \times 20°$$

$$\text{Celsius} = 0.556 \times 20°$$

$$\text{Celsius} = \mathbf{11.1°}$$

The average temperature in Loren's hometown will be about 11° C.

Converting to Degrees Fahrenheit to Degrees Celsius

Kerry was living in Japan when she got the flu. She felt as if she might have a fever, so she borrowed a thermometer from her neighbor and took her temperature to determine if she really needed to go to the doctor. When the time was up, she took the thermometer out of her mouth and looked at it. It said 38.1° C. Kerry is American and is used to degrees Fahrenheit, so she looked up the formula for converting the thermometer reading to degrees Fahrenheit:

$$\textbf{Fahrenheit} = \left(\frac{9}{5} \times {}^\circ\textbf{Celsius}\right) + 32$$

$$\text{Fahrenheit} = \left(\frac{9}{5} \times 38.1^\circ\right) + 32$$

$$\text{Fahrenheit} = (1.8 \times 38.1^\circ) + 32$$

$$\text{Fahrenheit} = 68.58^\circ + 32$$

$$\text{Fahrenheit} = \mathbf{100.6^\circ}$$

Kerry's temperature was 100.6° F.

Converting Degrees Celsius and Fahrenheit to the Kelvin Scale

Sabi is studying to be a scientist in the field of cryogenics. He is learning about the Kelvin scale and its use in measuring extremely low temperatures. He wants to practice converting some Celsius temperatures into Kelvin so that he is used to working with those numbers, so he uses the temperature of the human body in Celsius, 37.0° C:

$$\textbf{Kelvin} = {}^\circ\textbf{Celsius} + 273$$

$$\text{Kelvin} = 37.0^\circ + 273$$

$$\text{Kelvin} = \mathbf{310}$$

The temperature of the human body is about 310 K. *Note that the degree symbol is not used with the unit K.*

Sabi also converts the temperature of the human body from Fahrenheit (98.6° F) to the Kelvin scale. There is no formula for converting Fahrenheit to Kelvin directly, so it is a two-step process:

$$\textbf{Kelvin} = \frac{5}{9} \times ({}^\circ\textbf{Fahrenheit} - 32) + 273$$

$$\text{Kelvin} = \left(\frac{5}{9} \times 66.6^\circ\right) + 273$$

$$\text{Kelvin} = (.556 \times 66.6^\circ) + 273$$

$$\text{Kelvin} = 37.03 + 273$$

$$\text{Kelvin} = \mathbf{310}$$

The temperature of the human body is about 310 K. *Note that the degree symbol is not used with the unit K.*

How Does Heat Travel?

Why are pots and pans often made of copper? Why does a tile floor feel cold on your feet, but the wooden floor in the next room does not? Why would 212° F water burn your skin but reaching into a 350° F oven to baste a turkey not burn your arm? The answers to these questions are in this section and all have to do with how well the materials conduct heat and thermal energy.

Conduction

Conduction is the transfer of thermal energy without a transfer of matter. It occurs between materials that are touching, as particles collide and transfer energy. Conduction depends on how the particles in the substance behave. Remember that the particles in gases are farther apart. Conduction in gases is slower than in liquids and solids because the particles are far apart and do not collide as often. This is the reason that you do not get burned when you reach into the oven to baste a turkey. The air is obviously hot, but air is a poor conductor of thermal energy. In solids, particularly metals, conduction is faster because the particles vibrate or push against each other.

Thermal Conductors

Some materials conduct thermal energy well; these are called **thermal conductors**. Most pots and pans are made of copper, aluminum, or iron because they are good conductors. Look at the picture. The flame from the stove only touches the bottom of the frying pan, but the metal of the pan conducts the heat and spreads it throughout the pan to heat the food evenly. Notice that the handles of some pots and pans are metal too. Even though the flame does not heat the metal handle directly, it still gets hot. That is because the thermal energy is conducted through the metal.

Frying pans are made of materials that are good conductors of thermal energy.

A good thermal conductor does not have to result in warming an object. Have you ever walked across a tile floor in the summer? The floor is cool, even though the room might be very warm. Tile is a good conductor. It draws the thermal energy away from your skin. This means that the tile floor will be cool to the touch.

Think About It

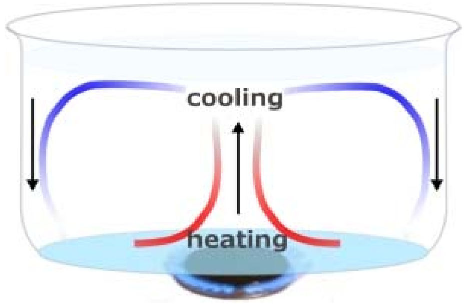
Look at the picture of the food cooking in the pan again. It would not be safe for you to touch the pan, and it would not be safe to grab the handle of the pan if it was made of uncoated metal. But you would be able to safely pick up the wooden spoon. What does that tell you about the wooden spoon's ability as a thermal conductor?

Thermal Insulators

There are also materials that do not conduct thermal energy well. A material that conducts thermal energy poorly is called a **thermal insulator**. Air is a very good insulator. This is why your coffee or hot cocoa does not burn your hands through a disposable cup. A foam cup is designed to trap pockets of air in the material of the cup. The air acts as an insulator and keeps thermal energy from passing through the material. Wool is a good thermal insulator, so blankets and sweaters are made out of it. Certain types of man-made materials inside gloves and winter jackets are good insulators because they not only keep thermal energy from escaping but they also reflect heat back to your skin.

Convection

Another form of heat transfer is convection. **Convection** is a transfer of thermal energy when particles of a liquid or gas move from one place to another. When a liquid or gas is heated, it expands and its mass decreases. The lighter, heated liquid or gas rises and the heavier, cooler liquid or gas sinks.



Convection in a heated pot

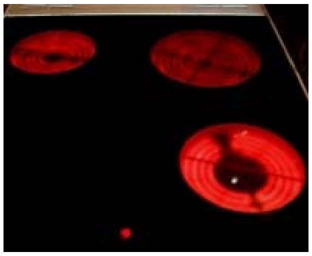
Look at the picture. The water in this pot is heating up. The water at the bottom, closer to the source of the heat, heats first. As this water heats up, it expands. Because there is more space between the particles after expanding, the water is less dense and its mass decreases. This newly heated water is lighter and rises to the top of the pot, leaving cooler, denser water at the bottom to begin its heating process. The cycle works in a circular motion.

Perhaps you have seen a radiator in a house. In spite of its name, radiators use the principles of thermal convection to work. A radiator forces hot air to rise up along the wall to the ceiling of the room. The cool air sinks to the bottom of the room and is forced back toward the radiator, where it will get heated. Because hot air rises and cool air sinks, radiators are usually placed on the floor and air conditioning vents installed near the ceiling.

Radiation

Radiation is different from conduction and convection because the materials do not have to be touching each other to transfer thermal energy. **Radiation** is the transfer of energy by waves that move through space. On a clear day when you walk outside, you can feel the warmth of the sun. The sun heats the Earth by radiation because space is a **vacuum** and there is no air between the sun and the Earth to transfer energy.

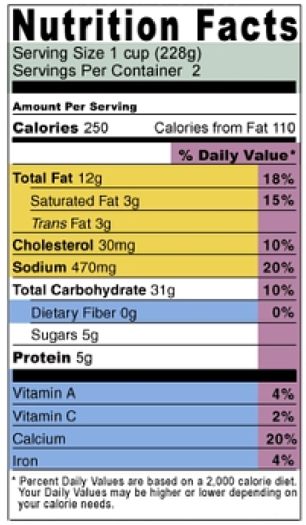
As the temperature of an object increases, the rate at which it radiates energy increases. All objects radiate energy, although some do it better or more efficiently than others. A stovetop heating coil gets extremely hot and radiates so much energy that it glows. Heat lamps radiate energy; they heat the food without touching it at all. If you stand close to the stove top or a heat lamp you are able to feel the heat, and you absorb the thermal energy as it warms you. The farther away you stand, the less heat you can feel, and the less thermal energy you absorb.


Stovetop coils glow red as radiation spreads out.

Thermal radiation is not the same type of radiation that would come from nuclear decay, although both types of radiation spread energy out from a source. The type of radiation that occurs with nuclear decay can transfer mass. Thermal radiation does not transfer mass, only energy.

How Do We Use Heat?

We use thermal energy in a variety of ways, many of them for measurement. Thermal energy's interactions with solids, liquids, and gases are predictable and therefore can be used in research and technology.



Find the calorie listing on this sample nutrition label for macaroni and cheese.

Calories

You may have already heard of an alternate unit to measure heat: the calorie. A calorie is the energy rating for food. It is a measurement of the amount of energy of a specific food as it is burned up by the body's metabolism. Calories are usually used to calculate the energy-producing value of food in a person's diet. Nutrition labels always include the amount of calories per serving.

Thermometers

Earlier in this lesson you read about a substance's ability to expand when heated. Traditional thermometers are based on thermal expansion. Remember that a heated substance takes up more room because the particles move around quickly and push against each other. Thermometers are filled with liquid that rises to show the temperature. If the liquid is red, it is alcohol. If the liquid is silver, it is mercury. When the outside temperature is higher than the liquid inside the thermometer, the tube heats up. The liquid expands and rises to a height that is proportional to the temperature.

Making Connections

This lesson focused on thermal energy, but thermal energy is only one type of energy. You will find throughout the rest of this course that energy is a property of many substances and also has to do with light, motion, electricity, sound, and many other aspects of physical science.

If your home has the type of thermostat with a lever that you move to set the temperature, then your thermostat works by thermal expansion. Many thermostats have a mechanism inside called a bimetal, or bimetallic, strip. This strip is made of two different kinds of metal that are bonded together. When the temperature rises, one metal expands more than the other, and the strip changes shape. The bending of the strip flips a switch that turns on the air conditioner. If your thermostat is digital, however, it uses a different type of control.

Energy is transferred in many ways, but over time the effect is that energy is spread out evenly. Throughout the natural world, what begins as a specific interaction ends up affecting many other parts of the world. Energy appears in many forms, and the transformation of energy usually results in some form of heat.

Important Formulas to Remember

$$\text{Celsius} = \frac{5}{9} \times (°\text{Fahrenheit} - 32)$$

$$\text{Fahrenheit} = \left(\frac{9}{5} \times °\text{Celsius}\right) + 32$$

$$\text{Kelvin} = °\text{Celsius} + 273$$

$$\text{Kelvin} = 5 \times (°\text{Fahrenheit} - 32) + 273$$