Insulation, Conduction, and Thermodynamics

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What does “R-19” mean on insulation?

If you ever went to the hardware store or helped build a house you probably worked with **insulation**. Different types of insulation are used in different portions of your house. For example, here in Georgia, in your ceiling and in the attics space on the roof, you should have insulation rated at least R-30, but R-38 is better. If you were in the north you would want at least R-38 but R-45 would really cut down on those energy bills. Back in the south, your walls should be rated at least R-13, but R-19 is better. The higher the R value the better the insulation, but what exactly is the **R factor** and how is it calculated?

R-value is defined as the temperature difference across the two surfaces (ΔT) multiplied by the area (A) by the change in time (Δt) divided by the **thermal energy** (Q) transferred between the two surfaces. In the U.S. we measure area by square feet, time in hours, temperature difference in degrees Fahrenheit and the flow of energy in BTU’s (**British thermal units**).

$$R = \Delta T * A * \Delta t \ / Q$$

Before we go any further, we need to look at what a “BTU” stands for. A BTU is a British Thermal Unit; each unit is defined as the amount of energy required to raise one pound of water by one degree Fahrenheit. This is roughly how much energy is given off when a kitchen match is struck and burned. You may be more familiar with other units of energy, such as the calorie or the joule. One BTU is about 252 **calories** or 0.252 **Calories** (the kind you read about on food labels) and is about 1,055 Joules. Or, if you look on your energy bill, you will find **kilowatt hours**. 1 BTU is about 0.00029 kW hrs.

So how much energy do you lose from your house on a hot Georgia summer day? Well, let us do a very rough calculation. Keep in mind that there are a lot of other factors involved that we are not going to worry about at this point in time. Let us imagine that we desire the temperature inside the house to be 75 degrees but it is 90 degrees outside. This means that the temperature difference is 15 Fahrenheit degrees. Let us assume a house is 50 feet long and 30 feet wide. This would give us an area of 1500 ft^2 if the roof were flat. However, it is at some angle so the area of our roof would have to be larger. Since angles are all different, let us just assume 2000 ft^2. With insulation of R-38, I want to know how much energy I lose each hour ($Q/\Delta t$).

$$R = \Delta T * A * \Delta t \ / Q$$

$$Q / \Delta t = \Delta T * A / R$$

$$= 15\ F^o * 2000\ ft^2 / 38\ ft^2\ F^o\ h\ /BTU$$

$$= 789.47\ BTUs / h$$

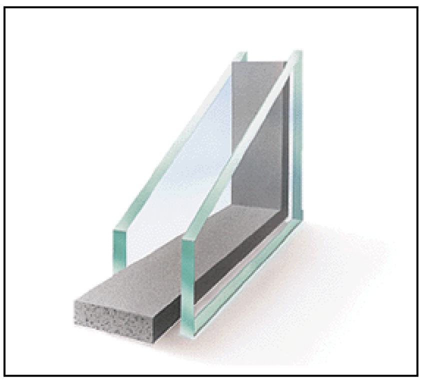
So, every hour about 790 BTUs flow from outside of the house to the inside. This is how much thermal energy you gain from the outside of the house. This is roughly 0.23 kW h. Energy companies typically charge about 4 to 8 cents per kW h. So you may think that it isn't that expensive to run the air conditioner but you need to keep a couple of things in mind. First, we only looked at the roof, but it turns out you lose the most energy from your windows. A single, one inch pane of glass only has an R value of 0.14. So if you have a 2 ft by 4 ft window (8 ft^2) that is one inch thick and is only a single pain of glass, for that same temperature difference, the amount of thermal energy transferred each hour is:

$$Q / \Delta t = \Delta T * A / R$$

$$= 15\ F^o * 8\ ft^2 / 0.14\ ft^2\ F^o\ h / BTU$$

$$= 857.14\ BTUs / h$$

Crazy huh? This is the main reason why most houses do not have single pane pieces of glass anymore. Most are double-paned **(Figure)**. This means that you have two pieces of glass with a vacuum in the middle. This panel can increase the R value to 30-50, a stunning increase over a single-pane window.



Caption: A cross-sectional view of a double paned window.
Source: http://www.vinyl-replacement-windows.com/images/content/install-replacement-windows.gif

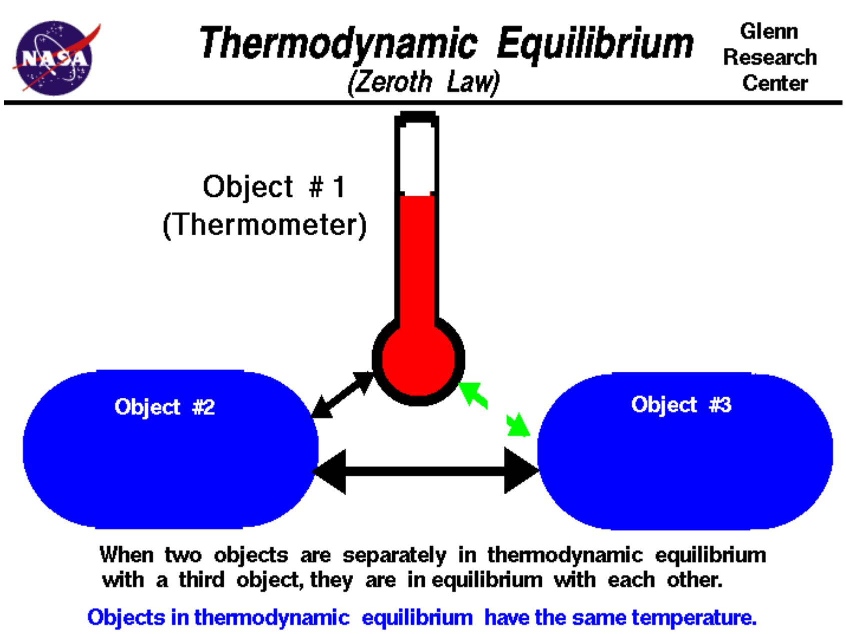
Second, in our calculations we made an assumption that the entire roof is nothing but insulation, but this isn't the case. The wood studs holding the roof up have a different R value then the insulation, so this must be considered in more detailed calculations. When we think about the entire house, realize that the side walls have a different R value then the roof as they are constructed differently and we haven't even calculated them. We also need to think about other places in which energy in lost, such as doors. This is why it is very important to make sure your house is properly insulated with high quality doors and windows and why you want to keep the door closed like your were always told as a child.

Rules govern how thermal energy gets from one place to another

The **laws of thermodynamics** relate to the flow of thermal energy from one object to another. These laws are some of the most fundamental in all of physics. You may have learned about the three laws of thermodynamics, but there are actually more than three. Through various observations and experiments our understanding of how the world works has changed, thus the laws of thermodynamics have changed over the years.

The fundamental Law that isn't the First Law: Zeroth Law of Thermodynamics

This law came about in the first part of the 20th century. Basically, this law states that if two different objects are in **thermodynamic equilibrium** (have the same temperature) with a third object, then all three objects are in thermodynamic equilibrium. Another way to put it is if the temperature of object A equals the temperature of object C and the temperature of object A equals the temperature of object B, then the temperature of B also equals the temperature of C **(Figure)**. This is a fundamental concept that wasn't explicitly stated until after the other three laws of thermodynamics were popular, and since it was the most fundamental of all three laws, it was named the **zeroth law**.

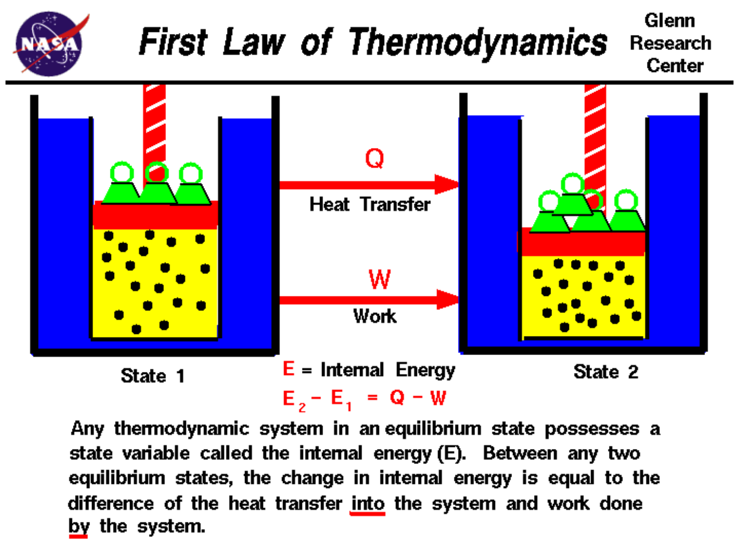


Caption: Object 1 is at the same temperature as Object 2 and Object 3, thus Object 2 and 3 are also at the same temperature.

Source: https://www.grc.nasa.gov/www/k-12/airplane/thermo0.html

Energy in equals energy out: The 1st Law of Thermodynamics

The **first law of thermodynamics** has several different variations depending upon the source. For some, you will see it stated as "energy cannot be created or destroyed, it only changes form under normal conditions." In other sources, you will see it listed as "In an isolated system, the total energy remains constant" or you may also see it listed as "the amount of energy lost by one object to a second one, is the same amount of energy that the second object gains" **(Figure)**.

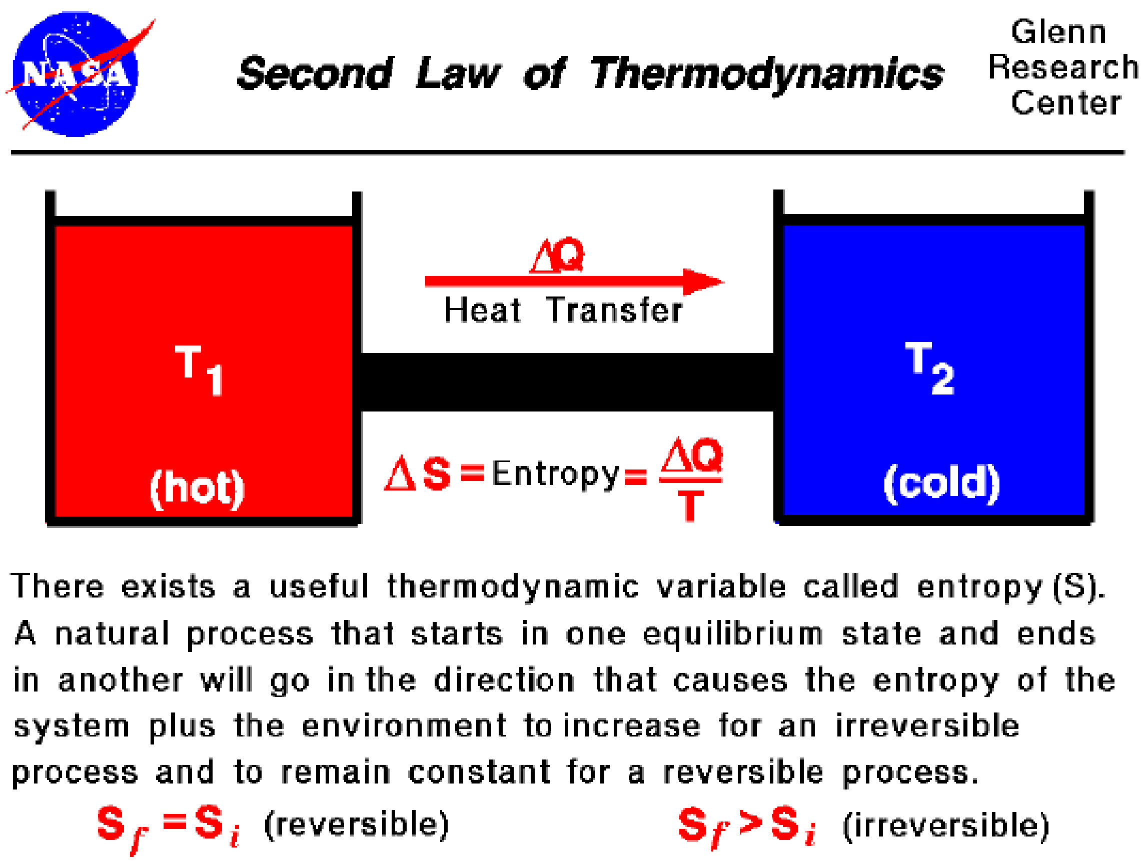


Caption: The energy leaving Slate 1 is equal to the work done by the system.
Source: https://www.grc.nasa.gov/www/k-12/airplane/thermo1.html

What this means is that if energy is leaving one substance and going into another, then the amount of energy that leaves the first object is equal to the amount of energy gained by the second object. Many forms of energy can transfer, not just thermal energy. Scientists once thought that different types of energy could not be transferred from one form to another. For example, thermal energy and energy gained from work (either potential or kinetic) were different. However, in the mid 1800's **James Prescott Joule** conducted an experiment showing that energy could be transferred between these two forms. He had a falling weight, which in turn moved a paddle underneath the water. The increase in thermal energy in the water matched the loss of the mechanical energy of the weights.

The flow goes from high to low: The 2nd Law of Thermodynamics

The second law of thermodynamics has two main definitions, although others exist. The first involves something we call **entropy**, which is a measurement of the amount of disorganization in a system. The first definition states: "In a system, a process that occurs will tend to increase the total entropy of a system". Another way to look at the second law is through the second main definition "Thermal energy does not spontaneously flow from a material at a lower temperature to a material at a higher temperature." **(Figure)**

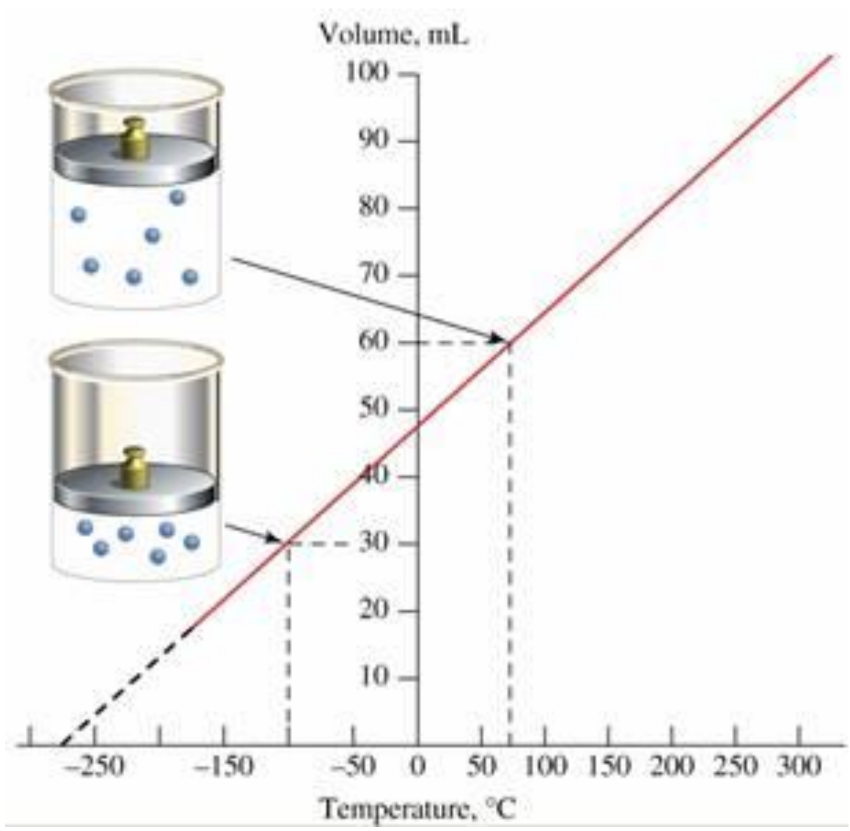


Caption: Since T_1 has a higher temperature than T_2, energy flows from T_1 into T_2.
Source: https://www.grc.nasa.gov/www/k-12/airplane/thermo2.html

Think about times that you have a picnic. You pack a cooler with ice in the bottom of the cooler. Why do you put ice in the cooler? The ice helps to keep all of the other food and beverages cold. Since the temperature of the ice is less than the temperature of the food, thermal energy flows from the food into the ice. This causes the temperature of the food to go down and the temperature of the ice to go up, which is why the ice melts and your food and drinks stay cold.

How low can you go? The 3rd Law of Thermodynamics

The third law of thermodynamics was proposed by **Walther Nernst** in 1906. He stated that the thermal properties of gases approach zero as the absolute temperature is approached, thus he believed that it was never possible to reach this **absolute zero**. So what exactly is absolute zero? Under normal conditions, almost all of the gases expand at roughly the same amount. They expand 1/273 (or about 0.37%) of their volume when temperature increases from zero to one degree Celsius. Conversely, gases will contract by the same amount in the reverse direction. When this relationship is graphed **(Figure)** there is a linear relationship.



Caption: A Volume versus Temperature graph showing absolute zero.
Source: http://www.eoht.info/page/Absolute+zero

The point at which the volume theoretically goes to zero is what we call absolute zero. This is also the point at which molecules stop moving. This became the basis of the Kelvin temperature scale. This scale was named after William Thomson also known as Lord Kelvin who first proposed it in 1848. The zero point on this scale is absolute zero (which is also – 273 ^{o}C and – 459 ^{o}F). The Kelvin scale has no negative numbers in it. Zero Kelvin is the lowest possible temperature that exists.

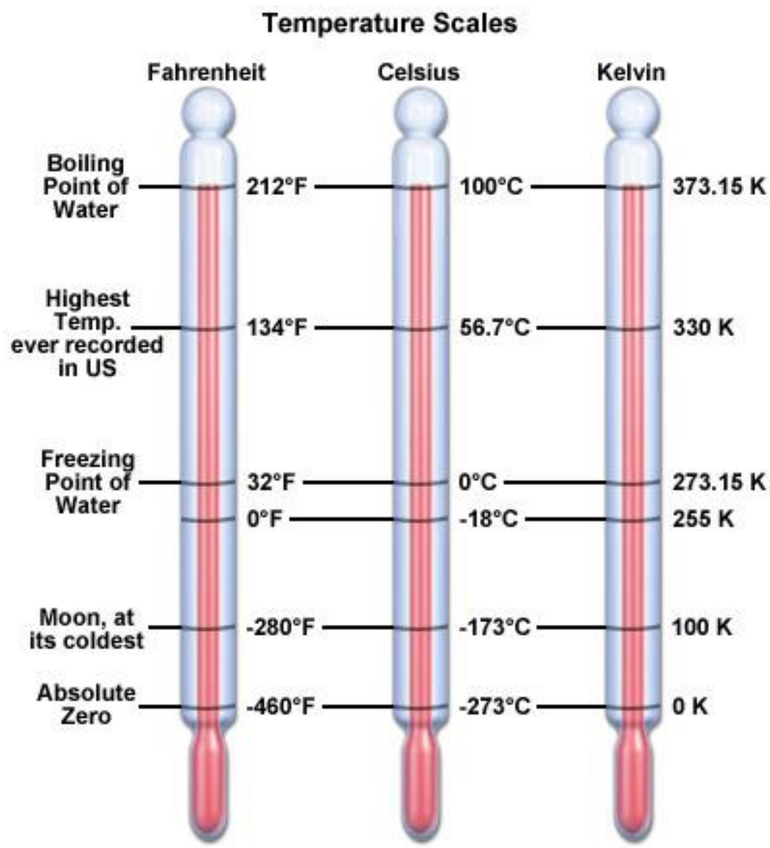
Heat is the flow of thermal energy

Many websites, textbooks and some state education standards erroneously list heat as a form of energy. Heat is not a type of energy; rather, it is the flow of thermal energy from one object to another. Think of heat as an action, a verb, not as a substance or rather as a noun. There are three main ways that thermal energy can flow from one object to another: conduction, convection and radiation. But first, it is important to know the difference between thermal energy and temperature.

Thermal energy and temperature are closely related, but not the same

Thermal energy is the total amount of energy in a substance due to vibrations, spinning or movement of the molecules. **Temperature**, on the other hand, measures the **average kinetic energy** of a substance. An example will help clarify this difference. Assume you have a cup of boiling water and a gallon of boiling water. In both cases, if you were to put a thermometer into the water, you would get a reading of about 100 ^{o}C, the boiling point of water. This means that the average amount of energy per molecule is the same whether it is in the gallon container or the cup. However, the cup contains far less water than a gallon. So the total amount of energy in the cup is less than in the gallon of water. Thus, the thermal energy is greater in the gallon than the cup.

There are three scales we typically use when we talk about temperature: Celsius, Fahrenheit, and Kelvin **(Figure)**. Anders Celsius proposed the Celsius scale in 1742. Initially, he had zero degrees as the boiling point of water and 100 degrees as the freezing point of water. This was soon reversed however, to the scale that we know today (though the baselines changed slightly in 1954 from the freezing and boiling points of water to absolute zero and the **triple point of water**).



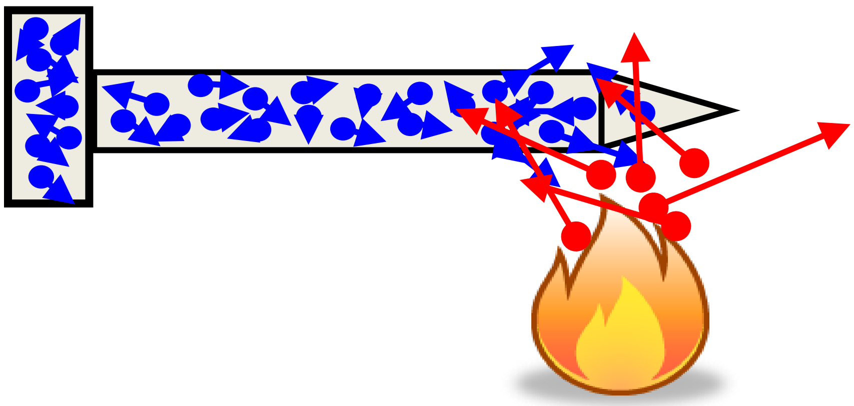
Caption: The three different scales with the temperatures that fresh water freezes and boils.
Source: https://climate.ncsu.edu/edu/Temperature

Daniel Fahrenheit also created a temperature scale a few years before Celsius did. In 1724 Fahrenheit published a journal with his proposed scale. His zero point was different then what Celsius used. Fahrenheit was able to lower the temperature at which water would freeze by adding salt to it. The lowest possible temperature he could achieve to freeze water was his zero mark. His high mark was 96 (six intervals of sixteen degrees) which was body temperature (or thought to be). When he placed the thermometer in his wife's mouth or under her arm, this was the recorded temperature. On this scale, normal water at normal conditions will freeze at 32 degrees and boil at 212 degrees.

Finally, the third scale is called the Kelvin scale. The zero on this scaled is based on absolute zero – the point at which particles stop moving. William Thomson, also known as Lord Kelvin published his paper in 1848 where absolute zero is the lowest possible temperature. This is the point where molecules cease to move. This is also the scale widely used in science.

Conduction is thermal energy transfer via direct contact

Conduction is the flow of thermal energy from one substance to another by direct contact. Look at the following figure of a nail being brought close to a flame **(Figure)**:



Caption: A picture showing the molecules in a nail speeding up due to the increased thermal energy.

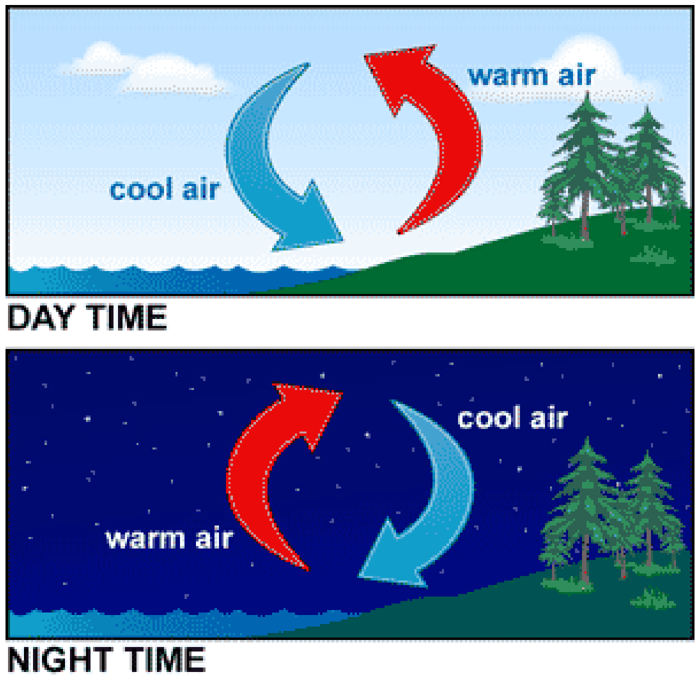
Imagine that each of the spheres in the figure represents a molecule, either air (red ones) or iron (blue ones) in the nail. The faster the molecules move (the longer the arrows), the more energy they have. When these molecules collide with one another, they transfer energy. The slower moving particles will now start to move faster, which means more energy. Thus, more thermal energy per molecule means a higher temperature.

There are many examples of this in everyday life. If you accidently touch a hot pan, the thermal energy from the pan will flow from the pan to you, causing pain and/or injury. If you put cans of warm soda into a cooler filled with ice, the energy will flow from the soda to the ice. In all of these cases, the materials are in direct contact, which allows the energy (but not the actual substances) to flow from one to the other.

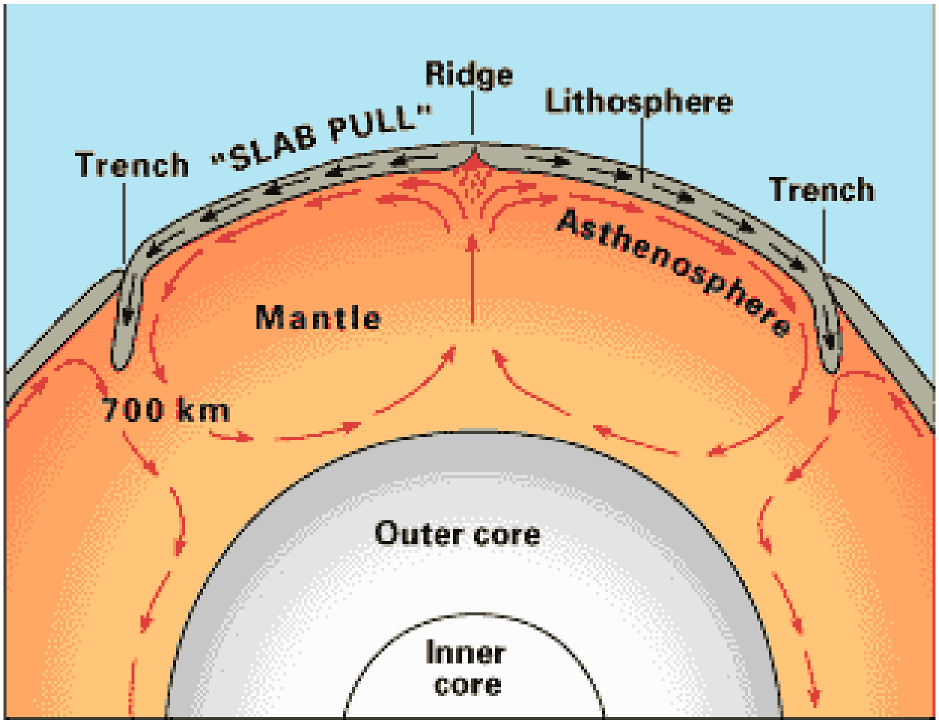
How well a material transfers thermal energy is called its **conductance**. If materials allow thermal energy to transfer easily, it's called a **conductor**, if thermal energy does not flow easily, it's called an **insulator**.

Fluids can transfer thermal energy by convection

Convection describes how fluids (which are gases and/or liquids) move from higher temperatures to lower temperatures. This process is common in nature. Examples include wind **(Figure a)**, boiling water, the Earth's core (plate tectonics and earthquakes) **(Figure b)** and within our Sun **(Figure c)**.

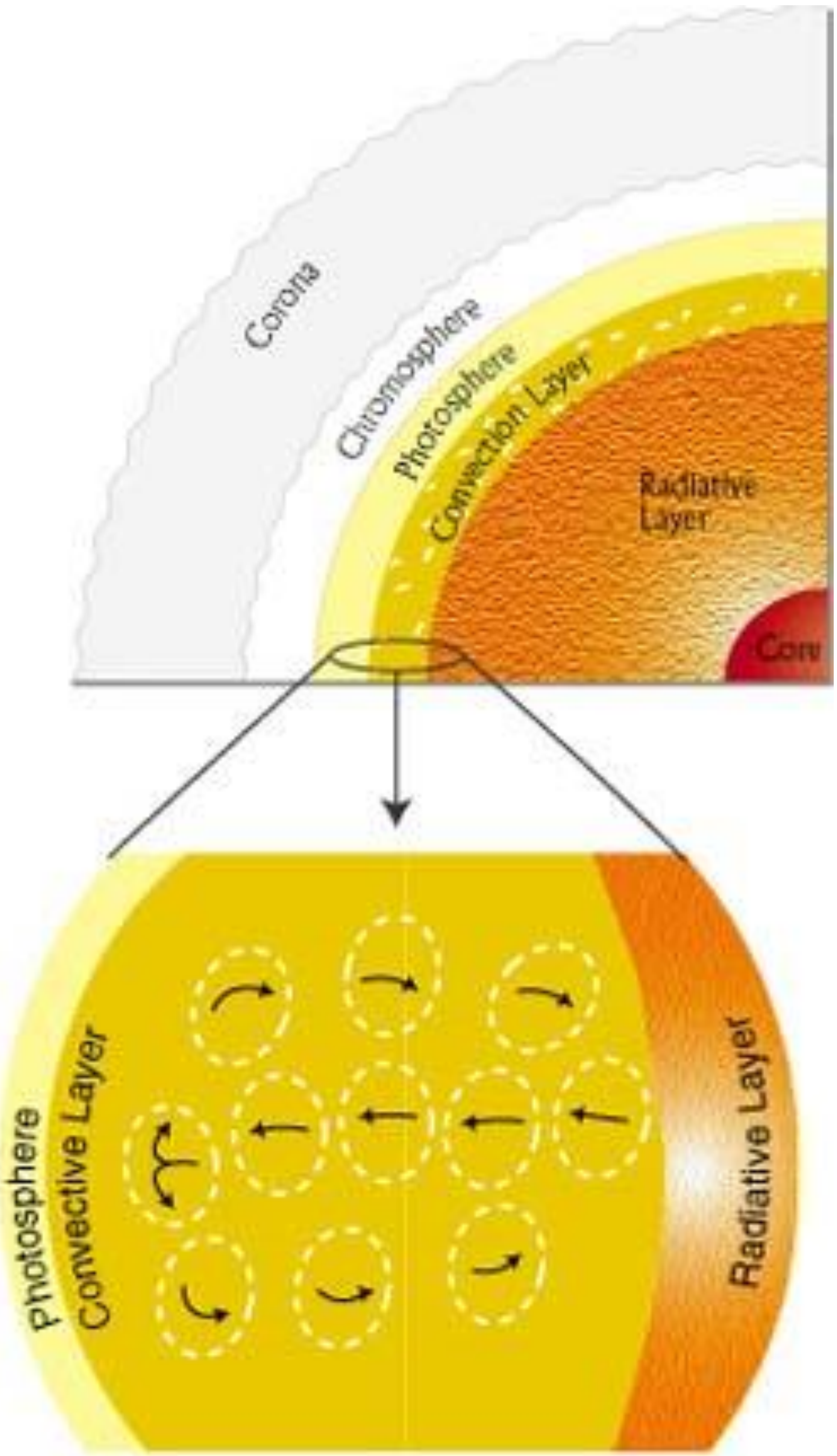


(a) Caption: Convection currents in the air.
Source: https://www.thinglink.com/scene/839536069509644292



(b) Caption: Convection currents within the Earth in the Mantle.

Source: https://en.wikipedia.org/wiki/Mantle_convection



(c) Caption: Convection currents within the Sun.

Source: https://genesismission.jpl.nasa.gov/science/mod3_SunlightSolarHeat/SolarStructure/index.html

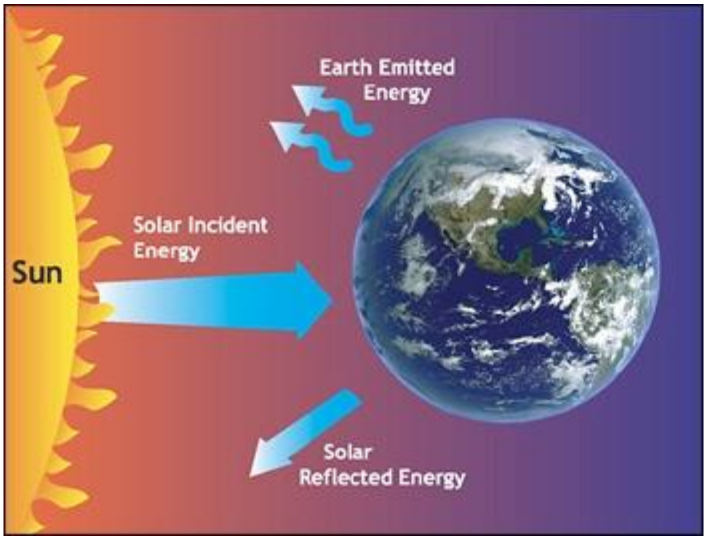
Convection is based on the idea that as the temperature of an object increases, it will expand. The same is true for the reverse. If an object's temperature decreases, it will contract. This will change the volume of the object but not it's mass. We don't gain or lose molecules of the substance; they just exist closer or farther apart. This will then affect something else very important - the object's **density**. Density is mass divided by volume:

$$D = m / V$$

If the mass stays the same, but the volume increases, then the density will go down (and vice versa). Thus, when the temperature of a liquid increases, it will expand (under most conditions) causing the density to decrease. This means warmer water has a lower density than colder water. So, if you put a pot of boiling water on the stove, as the temperature of the water at the bottom increases, its density decreases. The higher density water on top will push the lower density water to the top and then start what we call a "**convection current**." This process happens in the Earth's mantle, the atmosphere, and the Sun.

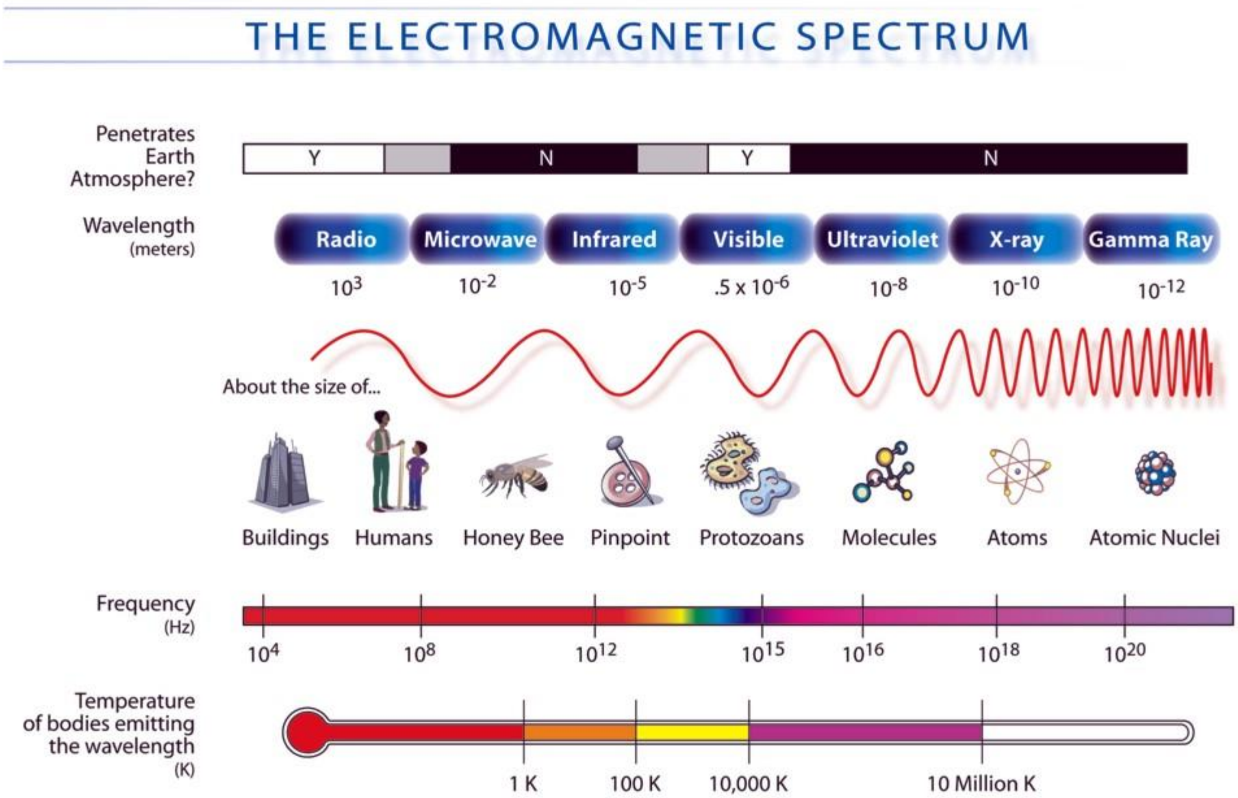
Radiation can transfer thermal energy in a vacuum

The final way that energy can be transferred is via **radiation**. All objects, including you and me, emit and absorb **electromagnetic radiation**. This is how we are able to get energy from the sun **(Figure)**. The sun emits electromagnetic radiation and we in turn absorb it, as does the Earth. When an object is in **thermal equilibrium** with its surrounding, it is emitting radiation at the same rate it is absorbing it.



Caption: The Sun emitting energy while the earth is also reflecting energy.
Source: https://www.nasa.gov/vision/earth/lookingatearth/ice_clouds.html

For most objects, the wavelength of electromagnetic radiation emitted is much longer than what is visible to the naked eye **(Figure)**. However, as the temperature increases, it does cross over into the visible spectrum. This is how astronomers are able to use colors to determine the surface temperature of a star. You may also know that a blue flame from a welding torch or stovetop is a much hotter flame then a reddish orange flame from a fire.



Caption: The Electromagnetic spectrum.
Source: https://mynasadata.larc.nasa.gov/science-practices/electromagnetic-diagram/