

Thermal NRG

You are probably well aware of the fact that when the temperature reaches 32°F (0°C) water freezes and turns into ice. When water reaches 100°C (212°F) it boils and turns into steam. The goals of this unit is to better understand why and how these events, and other related occurrences, take place as well as our perceptions of hot and cold.

We know that **temperature** is a measurement we use to tell us how hot or cold something is with respect to some standard. When we say our hands get warmer we mean the **temperature** is rising. But what is **temperature** *really* measuring?

Our everyday use of temperature simply gives us a reference frame for how hot or cold things are. We are familiar with the *Fahrenheit scale* here in the U.S., while most people in other countries use the *Celsius/centigrade scale*. These are both scales of relative hotness to chosen standards. Celsius is based on 0 degrees = freezing point of water and 100 degrees = boiling point of water. Then **100** equal divisions were marked off between these points, thus determining the range of 1 degree **centigrade**. The Fahrenheit scale was similarly determined with one degree F being smaller than one degree Celsius.

What **temperature** is actually measuring is a bit more complicated, but the basic idea is based on the actual *particles* that compose a material. Each particle has some potential (stored) and some kinetic (motion) energy. The total energy of a material is the total potential and kinetic energy of all particles in that material. This is often referred to as **thermal or internal energy**. The **temperature** is directly related to the average kinetic energy of all of the particles in a material. The temperature scale used for scientific research is the Kelvin (K) scale. This is an absolute temperature scale. An absolute temperature scale starts at zero degrees since the average kinetic energy of stationary particles would be zero. The Kelvin scale is basically a Celsius scale shifted so that zero represents absolute zero. As a result... $0^{\circ}\text{C} = 273.16 \text{ K}$ (no degrees)

Onward to the states of matter: **solid, liquid, gas, and plasma**.

A picture of a **solid** has all the particles packed tightly (high density) with motion due mostly to vibrations of the particles themselves.

A **liquid** shows loosely packed (density slightly less than solid) particles in which the vibrations have increased to the point where the particles can flow around each other.

A **gas** has spread out (almost no density) particles moving at fairly high speeds and numerous brief collisions.

So, in terms of the average kinetic energy, the solid should have the least and the gas the most. The simplest description of potential energy is based on the relative position of the particles. The solid would have the least potential energy and a gas the most potential energy. The total potential energy involves other factors, but the PE of position can give you a general idea of how PE changes based on state.

The change in density associated with a change in state generally follows the rule of **thermal expansion**: when heated matter expands; when cooled matter contracts. Water is one of the exceptions to this rule: liquid water expands when it freezes; ice contracts when it melts.

The **plasma** state contains particles that have started to break apart. A high temperature is not always necessary to produce the plasma state, just a high amount of energy.

For a solid substance to first melt, then boil, and possibly enter the plasma state a change must take place; this requires **energy** to be added to the particles. The reverse is true when changing from the plasma state back to the solid state.

If you consider the relative **temperatures** of these states you find a general increase from solid to gas. This means that a gas is *hot* and a solid is *cold*, relative to each other for the same material. The hot material represents more average KE than when it is cold.

Let's take a more detailed look at how materials heat up (or cool down) and change from one state to another: melting/freezing, vaporization(boiling)/condensation, sublimation, and evaporating are the changes we are most familiar with. Most people would agree that in order to melt a piece of ice you need to make it warmer or heat it up.

The basic principle here is energy transfer. When we say, "heat something up," we are describing the addition of **thermal energy** to a material in order to increase its temperature. To "cool something down," a material would require the opposite: the loss or removal of **thermal energy**. Both of these scenarios are defined, in the scientific sense, as **heat**: the flow or movement of **thermal energy** due to differences in **temperature**. Thermal energy naturally flows from regions of high temperature to regions of low temperature. Matter does not contain "heat".

A simple example would be a cup of hot coffee sitting on your kitchen counter. Eventually the coffee will be the same temperature as the kitchen. If the coffee is 180 °F (82 °C) and the kitchen air is about 72 °F (22 °C) there will be a flow of thermal energy from the coffee to the air. As a result the coffee cools while the air warms and when they reach the same temperature there is no more flow of thermal energy. This is called **thermal equilibrium**. The opposite happens with a glass of iced tea in your kitchen.

Now back to the ice cube...When you put some ice in a pot you have water as a **solid**. You can "heat" the pot on a stove which will cause it to warm to a higher **temperature**. The **temperature** difference between the burner and the pot results in **heat**, the **temperature** difference between the pot and the ice also results in **heat**, and so the **thermal energy** flows from the burner to the pot, then from the pot to the ice. This **thermal energy** causes the particles to vibrate faster, which increases the temperature measured. As the **temperature** rises, the particles are gaining kinetic and potential energy. Different materials need more energy to increase their temperature than others due to their composition. This property of matter is known as **specific heat capacity**. **Specific heat capacity** is the amount of energy required to change the temperature of a unit of mass of a material by 1 unit of temperature. It's kind of like thermal inertia, a material's tendency to stay at its current temperature. Materials with high specific heat capacities heat up and cool down slowly, or tend to resist change. Materials with low specific heat capacities heat up and cool down quickly, very little resistance to change. Water has a relatively high specific heat capacity (4.184 J/(g•°C) or 1 cal/(g•°C)).

The amount of thermal energy required to simply change the temperature of a substance, without changing state, can be found with the following equation, commonly known as the “heat equation”:

$$Q = m \cdot c_p \cdot \Delta T$$

Δ Thermal Energy = (mass)(specific heat capacity)(change in temperature)

As the temperature of your ice cube reaches 0°C the thermal energy provided causes the bonds between the particles to break. The temperature does not change during this process; instead all of the thermal energy is going towards the melting of the ice. When you have all liquid the added thermal energy will again cause the temperature to increase, indicating an increase in the average kinetic energy of the particles. Please note that during this real life situation the part of the ice in contact with the pot will melt first and start heating up, while the rest of the water is still frozen. The liquid water will increase in temperature until it reaches 100 °C, when it will boil (vaporize). Again the 100°C water will remain at 100 °C until all of the bonds holding the particles together are broken. At this point you have gaseous water, called steam or water vapor. In this example it would be hard for you to heat the steam since you cannot keep it in the pot. But if you could continue adding thermal energy to the steam, the temperature would then continue its upward trend.

The ice cube example involved frozen water at the start which heated up and underwent two changes of state: melting and vaporizing. During each change of state the temperature does not change, so the heat equation as written above is useless. Instead, we must use a similar equation which uses the substance’s heat of transformation. Heat of transformation is the amount of thermal energy required to change (transform) a substance from one state to another. The term heat of transformation is used less than the more specific terms: heat of fusion (freeze/melt) and heat of vaporization (vaporizing/condensing).

The amount of thermal energy required to change the state of matter can be found with the following equation:

$$Q = m \cdot L$$

$Q = (\text{mass})(\text{heat of transformation})$

$L_f \equiv$ heat of fusion

$L_v \equiv$ heat of vaporization

All parts of the ice cube scenario dealt with heating up the water. All of the processes can be reversed to explain cooling water vapor down until it is ice. In either situation, you are changing the amount of thermal energy in the water and its surroundings. During heating you add energy to the water, which must come from the surroundings. During cooling you must remove energy, which then is gained by the surroundings. This is simply the law of conservation of energy: you cannot create or destroy energy. Therefore, if you add energy to one material another must be losing that same amount of energy.

There are three basic processes that allow energy to transfer from one location to another: **conduction** (particle contact), **convection** (fluid motion), and **radiation** (electromagnetic waves). The example of melting the ice in a pot was conduction, more specifically **heat conduction**.

Heat conduction is the transfer of thermal energy through the collisions of particles in the material(s) due to a difference in temperature. Solids are generally better **conductors** since the particles are closer together and metals are usually good conductors because of the "freedom" of the electrons in a metal. It is not wise to hold a metal rod over a heat source for long, the heat will reach you fairly quickly. Poor conductors such as wood, asbestos, glass, plastic, air, and water are called **insulators**. **Insulators** are materials that do not allow energy to be transferred easily. Something that reduces the formation of **convection** currents would also be considered an insulator.

Convection is a method of energy transfer due to the movement of large amounts of a material; this flow is called a **convection current** and is most often seen in liquids and gases. As air is heated it will expand (**thermal expansion**) as it expands, its density decreases and the warmer air rises through the cooler, denser air. Meanwhile, the cooler air falls to where the warmer air was before heating. This cooler air is then heated resulting in the same **convection** process. Water is a fluid and undergoes convection when heated or cooled. Convection makes boiling water much easier and faster. Think how long it would take to conduct all the energy necessary through an insulating material like water. Convection is also very much a part of our weather, heats our homes, allows marine life to survive during the winter months, etcetera.

The third path for energy is the most prevalent but often the least noticed and understood, **radiation**. **Radiation** is simply the transfer of energy through electromagnetic waves. Do not confuse this with radioactivity of a material. Harmful radiation (UV, X-rays, gamma/cosmic rays) is only part of the electromagnetic spectrum, which also includes radio, TV, microwaves, infrared, and visible light. Irradiated foods have not been exposed to radioactive materials in the uranium, plutonium sense. As a matter of fact, if you microwave your dinner you have irradiated your dinner with *microwaves*. A picture showing the different temperatures on a human body is created by measuring the **infrared radiation** given off by the body. The amount of infrared radiation given off is directly proportional to the temperature of the body at that location. Colors are then assigned to the amount of infrared radiation given off, and by comparison the temperature. **Radiation** is the only process of energy transfer that does not require a material for the energy to travel through. Radiation can travel through the vacuum of empty space. However, each type of radiation has materials that it can and cannot travel through. Some materials simply absorb the energy. For example, ultraviolet radiation goes through clouds like there is almost nothing in the way, but it cannot pass through clear glass.