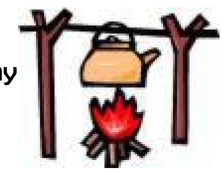
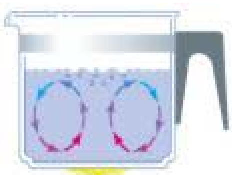
Convection, Conduction & Radiation

There are three basic ways in which heat is transferred: convection, conduction and radiation. In gases and liquids, heat is usually transferred by convection, in which the motion of the gas or liquid itself carries heat from one place to another. Another way to transfer heat is by conduction, which does not involve any motion of a substance, but rather is a transfer of energy within a substance (or between substances in contact). The third way to transfer energy is by radiation, which involves absorbing or giving off electromagnetic waves. As long as there is a temperature difference in a system, heat will always move from higher to lower temperatures.



A campfire is a perfect example of the different kinds of heat transfer. If you boil water in a kettle, the heat is transferred through convection from the fire to the pot. Heat is conducted along the handle of the pot, which is why you need to be careful picking the pot up, and why most pots don't have metal handles. In the water in the pot, convection currents are set up, helping to heat the water uniformly. While watching the campfire you feel the heat of the glowing fire via radiation.

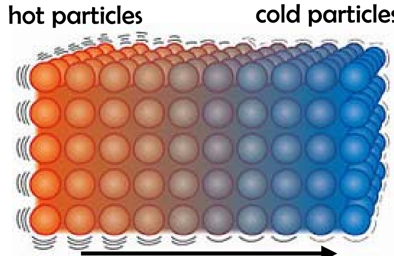
Convection



Heat transfer in fluids generally takes place via convection. Convection currents are set up in the fluid because the hotter part of the fluid is not as dense as the cooler part, so there is an upward buoyant force on the hotter fluid, making it rise while the cooler, denser, fluid sinks. Birds and gliders make use of upward convection currents to rise, and we also rely on convection to remove ground-level pollution.

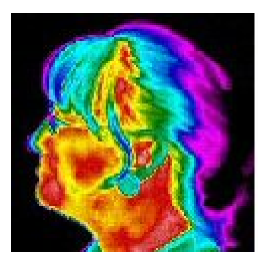
Conduction

If one end of a solid object, a piece of metal for example, is heated, the heat will pass through to the cooler end. The faster molecules, which are hotter and have a greater kinetic energy collide with the slower moving cooler molecules that have a lower kinetic energy. The transfer of kinetic energy causes the cooler molecules to heat up (speed up), while in turn the faster molecules slow down and become cooler.



Radiation

Radiation, in this context means light (visible or not). Heat is transferred, for example, from the sun to the earth through mostly empty space - such a transfer cannot occur via convection nor conduction, which requires the movement of material from one place to another or the collisions of molecules within the material.

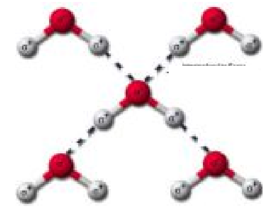


Often the energy of heat can go into making light, such as that coming from a hot campfire. This light, being a wave, carries energy, so it can move from one place to another without requiring a medium. When this light reaches you, part of the energy of the wave gets converted back into heat, which is why you feel warm sitting beside a campfire. Some of the light can be in the form of visible light that we can see, but a great deal of the light emitted is infrared light, whose longer wavelength is detectable only with special infrared detectors. The hotter the object is, the less infrared light is emitted, and the more visible light. For example, human beings, at a temperature of about 37 ° Celsius, emit almost exclusively infrared light, which is why we don't see each other glowing in the dark. On other hand, the hot filament of a light bulb emits considerably more visible light.

Convection, Conduction, Radiation Potpourri

Located around the room are various stations that demonstrate concepts related to thermal energy. Conduct the investigation at each station and provide a description and explanation for your observations.

Station #1: Evaporation



Liquids undergo a phase change to a gas when sufficient heat energy is provided to help break intermolecular bonds between molecules. This allows them to free themselves from the attractions of other molecules to turn into a gas. Evaporation of a liquid is a similar process but occurs much slower and at lower temperatures than boiling. In each process the liquid absorbs heat. The stronger the intermolecular bonds the more heat energy is needed to break the bonds.

- Place a drop of water and a drop of alcohol on the back of your hand. Blow gently across the top of the liquids. What differences do you feel when the two liquids evaporate?
- The two liquids are the same temperature. Why does your hand feel different for the two liquids? What supplied the energy to evaporate the liquids?
- Which liquid evaporated first? What are the differences in the attractive properties between molecules of the water and alcohol?

Both the water and the alcohol are the same temperature (room temperature), however the intermolecular forces between alcohol molecules are not as strong as those for water molecules. This means that kinetic energy added to alcohol molecules will break with less heat than the intermolecular bonds in water. Your hot (high KE) skin molecules collide with and transfer KE to alcohol molecules, increasing their velocity breaking the bonds between molecules. Evaporation of the liquid alcohol to a gas carries KE away and your skin molecules ultimately lose KE, therefore your skin feels cool. This is also true for when you sit in front of a fan on a hot summer day. The fan increases the rate of perspiration evaporating off your skin, carrying away KE leaving your skin with less KE. The fan does not produce cool air, it only feels like it.

Station #2: The Love Meter

The pulse bulb (Love Meter) contains a colored alcohol similar to the alcohol you used in the previous station. Place one hand on one of the bulbs to move the liquid to the other side of the bulb. Rub your hands together to warm them up and try it again. Does the liquid flow from the warm end of the bulb or to the warm end of the bulb?

- Hold the pulse bulb in the center and place a couple of drops of alcohol on one end of the bulb.
- Blow across the top of the bulb which you placed the alcohol. Which way does the liquid flow this time? Which end of the bulb is warmer?
- Explain how the heat of your hand can move the liquid to the other side of the bulb. (Hint: This is similar to what happened to the alcohol in the previous station.)
- Explain why the application of alcohol to one end of the pulse bulb can have the opposite effects of heat.

Hot (high KE) skin molecules collide with and transfer KE to glass molecules; high KE glass molecules collide with and transfer KE to air molecules. High KE air molecules collide with the orange liquid molecules and the liquid evaporates. When a liquid evaporates there is a large increase in volume as it changes to a gas. As the volume increases the pressure inside the pulse bulb increases, forcing the orange liquid to the other side. Since evaporation is a cooling process, putting a drop of alcohol on the glass causes the glass molecules to lose KE which causes the air molecules to lose KE which causes the vapors of the orange liquid to condense. As the gas condenses to a liquid on the cooler side, a decrease in pressure occurs. Since the opposite side of the pulse bulb in higher in temperature and higher in pressure, the orange liquid is pushed from the high pressure side to the cooler low pressure side of the pulse bulb.

Heat is not a substance, it is a property of a substance. When an object moves in response to a change in temperature, something must be pushing or pulling the object causing it to move. Heat cannot move an object.

STATION #3: THERMAL CONDUCTIVITY

Different substances are able to absorb heat at different rates and to different amounts. Materials that absorb heat rapidly are conductors. Materials which do not absorb heat energy are nonconductors, or insulators. The four pieces of material are all at room temperature. Notice that they feel different when you place your hands on them. Place them in order in terms of their apparent temperature from "warmest" to "coldest".

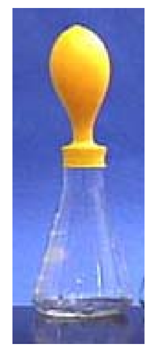
- What direction is the heat flowing when you touch each material?
- Provide an explanation of why they feel different to the touch if they are the same temperature.

All of the materials are at room temperature (about 20°C) while your skin is between about 35°C and 39°C. Each of the materials is absorbing your skin molecules' KE through collisions. However, through collisions the materials transfer this extra KE away from your skin at different rates – hence, the thermal conductivity of each tile is different. The aluminum feels the coolest to your brain because it is transferring the KE away most rapidly and has the highest thermal conductivity. The wood and the fur are poor thermal conductors, or better thermal insulators than the aluminum.

STATION #4: PRESSURE

As heat is applied to a substance the energy of the particles of the substance increases. This causes the molecules to vibrate, rotate, and move from place to place more rapidly. As the kinetic energy of the particles increases, they collide with each other and with the walls of the container. The spaces between particles also increases.

The reading on the pressure gauge is an indication of the average kinetic energy of the molecules trapped in the silver ball. If the molecules are speeded up, they can make a greater number of collisions in a given amount of time with the walls of the container and with each other. This increases the pressure (force per area) inside the container. Decreasing their average velocity results in fewer collisions per time, and the pressure decreases.



- Plunge the ball in the heated water and watch the reading on the pressure gauge change.
- Now place the ball into the ice water. What happens to the reading of the pressure gauge? Explain your results.
- Place the flask with the inflated balloon into the ice water. What changes are occuring to the air molecules in the flask to explain the changes in the balloon?
- Place the flask into the hot water. What is happening at the molecular level to the air in the flask to explain the changes in the balloon?

Inside the metal ball are air molecules; the KE of these air molecules determine the reading of the pressure scale. Placing the ball in hot water causes (through collisions) the transfer of KE from the water molecules to the metal molecules. (The last sentence can be more efficiently written as: KE is conducted from the hot water to the metal ball.) Then KE is conducted from the metal ball to the air. As the KE of the air molecules increases, the pressure gauge goes higher and higher. Pressure of a gas is determined by the number of collisions taking place within the metal sphere. As the temperature increases, the KE of the air particles increase and the number of collisions increases, increasing the pressure. As the temperature decreases, so does the KE and so does the number of collisions inside the sphere.

STATION #5: THERMAL EXPANSION

Heat has a similar effect on solids as it does on gases and liquids. The attraction of particles in a solid are greater than in liquids or gases. When the temperature of a solid increases, changes in the particles' kinetic energy also occurs and the solid expands. Try moving the ball through the ring. Now heat the ball in the flame and try it again. What are your observations?

- Allow the ball to cool. Now heat the ring instead of the ball. What happens to the size of the hole?

When a material is heated the average KE of its molecules increases; this means that the average distance between molecules becomes greater and the material expands; the ball get larger and the ring hole gets larger (all dimensions of the ring expand). When the ball is heated it will no longer fit through a cold ring unless the ring is also heated. A heated ring will easily pass a cold ball.

STATION #6: DIFFERENTIAL EXPANSION

Different substances expand different amounts when heated. The strip of metal is actually composed of two different metals, steel and brass. Heat the bimetallic strip in the flame. Which metal exhibits a greater expansion when heated? Explain your observations based on the differential expansion of the metals.

- Turn the bimetallic strip over and place it over the flame. Does it bend in the same direction as it did before?

  A bimetallic strip consists of two dissimilar metals bonded together; when the strip is heated, both metals are at the same temperature because KE is transferred quickly between them. However, at the same elevated temperature one of the metals will expand more rapidly than the other, thus, the strip will always bend away from this rapidly expanding metal and bend toward the other metal. The metal with the larger expansion will be on the outside of the curved bimetallic strip.

STATION #7: RADIANT HEATING

Heat is not all black and white. Technically speaking, black and white are not colors at all. Black is the absence of all color, while white is the presence of all colors. Similarly, white substances absorb all photons in the electromagnetic spectrum and reflect all colors (visible photons). Black absorbs all photons in the electromagnetic spectrum and reflects no visible photons. Record the readings of the thermometers placed on the black and white cards.

- How do you account for the differences you observe.

  The thermometer on the black paper indicates a more rapidly rising temperature. Although both white and black paper absorb photos from the lamp, the white paper reradiates visible light photons and releases energy. The black paper reradiates infra-red photons (invisible to us), but the energy content of these IR photons is much smaller than visible photons. That is why one should wear white colored clothes in July.

STATION #8: THE RADIOMETER

Heat from the sun passes through space before it passes through the atmosphere to warm the earth's surface. Neither convection nor conduction is possible in the empty space between our atmosphere and the sun, so heat must be transmitted some other way - by radiation. Radiant energy occurs in the form of particles of energy called **photons.** Infra-red radiation is composed of photons which radiate heat energy, while visible radiation, or visible light is composed of photons of higher energy than infra-red radiation.

The glass bulb with the black and silver vanes is called a radiometer. Turn on the incandescent lamp and observe the direction of the vanes inside the radiometer (white vanes in front or black vanes in front). Record your observations of the direction in which the vanes are moving.

- Next, turn on the lamp which has the filter attached to it. This filter filters out the visible light photons and allows only infra-red photons to pass through. Hold your hand up to the filter and feel the infra-red photons. Hold the light next to the radiometer and record your observations.
- Next, turn on the fluorescent light. Compare the effects of the incandescent lights with the florescent light. What differences are there in the photons emitted by the two light sources?
- If both sides of the vanes were painted black, woiuld this change the motion of the radiometer? How?
- If the air were evacuated from the radiometer, would this change the motion of the radiomer? How?

  If photons are absorbed by the black vanes inside the glass envelope of the radiometer, it will spin. The incandescent bulb emits photons of all visible energies and many, many low energy IR (heat) photons so the radiometer spins rapidly, the fluorescent bulb does not emit many of these IR photons and so the radiometer spins hardly at all. This, by the way, is why fluorescent bulbs are energy efficient. Even placing a filter that only transmits IR photons in front of the bulb has little effect on the spinning. The heater emits IR photons at all and so it also causes the radiometer to spin. The mechanics of how the radiometer spins is quite difficult to explain, but what is necessary for spinning is that one side of the vane must absorb photons and the other must reflect photons, and that the inside of the radiometer

must contain air. As the black side of the vane becomes hot, the air near the black side of the vane expands causing a greater pressure on one side of the radiometer. Without air, or if both sides of the vane were either black or silver, the radiometer would not spin.

STATION #9: GALILEAN THERMOSCOPE

The origin of the thermometer can be traced to the work of Galileo, who constructed the first "thermoscope". Benedetto Castelli wrote in 1638 about a device he had seen in Galileo's hands around 1603:

> "He took a small glass flask, with a neck about two spans long [perhaps 16 inches] and as fine as a wheat straw, and warmed the flask well in his hands, then turned its mouth upside down into the a vessel placed underneath, in which there was a little water. When he took away the heat of his hands from the flask, the water at once began to rise in the neck, and mounted to more than a span above the level of the water in the vessel. The same Sig. Galileo had then made use of this effect in order to construct an instrument for examining the degrees of heat and cold."

It was not until almost 20 years later, however, that a colleague of Galileo suggested adding a scale to the thermoscope to make the first thermometer.

- Note the level of the liquid in the glass tube. Vigorously rub your hands together to warm them and place them on the flask and observe the motion of the liquid within the column. What is responsible for the motion of the colored liquid within the column? (Hint: What pushes it?)
- Now place several drops of alcohol on the flask and blow across it. Note the direction the liquid moves. What happens to the temperature of the air inside the flask? What is responsible for the motion of the colored liquid?
  Placing your hands on the glass flask increases the temperature of the air inside and causes the air to expand. It is this expanding air that pushes the water in the glass tube downward. When alcohol is placed on the flask, the alcohol evaporates and cools the air inside the flask. As the air decreases in volume it decreases the pressure in the flask. It is the atmospheric pressure outside the flask pushing down on the liquid in the small beaker at the bottom that pushes the liquid up the tube.

STATION #10: CANNED HEAT

"Hotness" is a property of an object called temperature. Temperature is a property of matter; it does not depend upon the quantity or type of a substance, only the average kinetic energy of the particles. When light strikes an object, the motion of its particles speeds up as varioius wavelengths of light are absorbed. The more energy absorbed, the more kinetic motion and the light the resulting temperature. Objects that absorb more energy tend to be warmer than objects that reflect energy.

Set A: Earlier in the period the cans were filled with room temperature water and the light was placed in front of the cans so that they are equally illuminated. Which can is at a higher temperature? Record the time and temperature of each of the cans below and also in the data table on the board.

Set B: Earlier in the day the cans were filled with hot water. Record the time and temperature of each of the cans below and in the data table on the board.

On a sunny winter day what coat – black or white – might be warmer? Explain your reasoning.

On a sunny summer day what shirt – black or white – might be cooler? Eplain your reasoning.

Black is a good absorber as well as a good emitter of radiant energy (photons). As you saw in previous stations, black absorbs infra-red photons, therefore the black can heats up faster than the silver can which reflects these photons. The black can is also a better emitter of photons, so it cools faster than the silver can because it cools not only by conduction (both silver and black cans conduct heat this way) but the black can also cools by radiative cooling.

The air molecules over the candle flame have increased KE, increased volume and decreased density so they rise through the cooler, more dense air molecules above them. The cooler, denser air molecules under the other chimney move into the vacated area and ultimately a macroscopic *convection current* is created: air molecules rise over the flame and fall down the other chimney toward the flame.