Hot Cans and Cold Cans

Synopsis

Students will investigate and apply the simple physics of heating and cooling to a controlled situation requiring that they keep one mass of water warm, and cool another, equal mass of water, using only common everyday materials.

Objectives

Students will be able to give operational definitions of the three types of heat transfer: conduction, convection, and radiation. They will also be able to describe ways people try to use or try to prevent heating and cooling by conduction, convection, and radiation in everyday life.

This exercise addresses Competency Goal 4 of the *NC Standard Course of Study* for sixth-grade science, "The learner will investigate the characteristics of energy transfer." It specifically meets Objectives 4.10 and 4.10, "Determine how convection and radiation transfer energy," and "Analyze heat flow through materials or across space from warm objects to cooler objects until both objects are at equilibrium."

This exercise also reinforces Competency Goal 4 of the *NC Standard Course of Study* for seventh-grade science, "The learner will build an understanding of the general properties and interactions of matter." It specifically addresses Objective 4.01, "Relate state of matter to the arrangement and motion of atoms or molecules"; Objective 4.03, "Analyze the suitability of materials for use in technological design: conductivity"; and Objective 4.05, "Describe and measure quantities related to chemical/physical changes within a system: temperature."

Procedure

Students should work in teams of four, if possible. Each team will be given two identical soda cans, both filled with water at about 35°C. Each team's task is to get the water in one of their cans as cool as possible in 30 minutes, while keeping the other as warm as possible for the same amount of time. Each team must record the temperatures inside both cans every 5 minutes.

Start by providing a table full of useful junk, such as scraps of fabric (various sizes), socks from the lost & found, packing peanuts of several types, pieces of foam (various sizes), construction paper (both light and dark colors), bubble wrap, newspapers, quilt batting, old overhead transparencies, rubber tubing, drinking straws, funnels, aluminum foil, large zipper-type plastic bags, and anything else you can think of that could be used as insulating or conducting material, or material that will absorb or reflect radiation. Be sure to provide ample scissors, string, glue, tape, and staples as well.

You may want to impose some limitations on the types of materials used. For example, it is a good idea to forbid human-made containers or devices such as lunch boxes, thermoses, flashlights, classroom radiators or air conditioners. (The idea is for students to "start from scratch" rather than use existing technology.) Obviously, flames would not be allowed. You may or may not allow water to be used, and if so, you will have to decide what temperature the water may be, e.g., room temperature or 35°. Do not let students pour out their 35° water and replace it with hot or cold water from the tap! In fact, you might want to require that the original water stay in the can for the duration of the experiment.

Let the students examine the materials first and plan their cooling and warming devices. Allow time for construction, probably about 20 minutes, and when all are ready, issue the water-filled cans and thermometers. The cans can be kept submerged in a sink full of warm water until the class is ready. Each team should have one thermometer for each can if at all possible. If they need to share one thermometer between their two cans, be sure they wait 2-3 minutes before reading the thermometer after switching between cans. Standard laboratory liquid thermometers accurate to 0.5 or 1°C are recommended. If possible, issue a timer to each team or otherwise let the students be responsible for keeping track of their 5-minute intervals.

In addition to the student cans, fill two or three additional cans with the 35° water and leave them sitting in a central location. These will serve as controls; the temperatures in these cans should be checked at the same 5-minute intervals. (This can be the teacher's responsibility, or the task can be assigned to a student.)

Discussion and Further Investigation

Ask each team to explain its heating and cooling devices to the rest of the class, and report on how successful the devices were. Be sure to compare their results to the temperatures of the control cans. A good way to do this is for students to graph the changes in temperature over time for their two cans, along with one of the control cans, all on the same set of axes. After comparing their graphs, ask the students to identify common elements found in the warming devices, and then do the same for the cooling devices. Ask students where they got their ideas for each type of device, and then ask if they can explain *how* their devices worked. This would be a good time to introduce the concepts of heat transfer by conduction, convection and radiation.

Heat Transfer by Conduction

Conduction is easily demonstrated by handing a metal spoon that has been kept in a cool place to a student, and asking him or her to describe how it feels. The student will undoubtedly report that it feels cold. The reason it feels cold is that heat is flowing from the student's warm hand into the cooler spoon. Heat *always* moves from warm objects to cooler ones, and continues to do so until both objects come to equilibrium at the same temperature. So, if one student holds the spoon long enough, he or she can then hand it to another student, who will report that the spoon feels neither hot nor cold.

Conduction works because molecules are always in motion. Consider water molecules, for example. Water is in a liquid state between 0° and 100° C. At room temperature, the individual molecules are constantly bouncing off each other; this motion is driven by the heat present within the system. If we raise the temperature of the water by applying more heat, we can get the molecules to bounce off each other faster and faster, until at 100° they are bouncing so energetically that they can escape the water surface in the form of steam. In this gaseous state the molecules are less densely packed together, and they have to travel further before they collide, but because they have lots of heat energy, they are still moving about very quickly.

However, if the water is cooled from room temperature, the molecules move more slowly. At the point where water freezes -- and therefore becomes a solid -- the molecules have slowed so much that instead of bouncing off one another, they are only vibrating in place. (They will continue to do so, but more slowly, until the temperature falls to -273° C. At this point, known as absolute zero, molecular motion ceases altogether, at least in theory.)

In heat transfer by conduction, when heat is applied to one end of a solid such as a metal spoon, the molecules comprising that metal begin to vibrate more vigorously than their unheated neighbors. In solids the molecules are very tightly packed together. Therefore, the more energetic vibrations of the heated molecules make them bump against their neighbors, causing them to vibrate more quickly as well. These, in turn, cause their adjacent molecules to vibrate more vigorously, etc., until the heat has been distributed throughout the spoon. When you pick up a metal spoon, heat from your warm hand is enough to get this process going.

Some materials are better conductors than others. Metals are especially good, but glass and ceramics aren't bad either. Plastic and wood are relatively poor conductors, which is why wooden spoons are good for cooking and saucepans have plastic handles. You can demonstrate the relative conducting abilities of different materials by placing a large metal spoon in the left hand of a student, while placing a similarly-sized wooden spoon in his or her right hand.

Conduction also happens in liquids, and in general, liquids are good conductors. Furthermore, conduction occurs between liquids and solids, which is how the soup gets hot after the pot does.

Heat Transfer by Convection

Conduction in gases is not very efficient because the molecules are so far away from each other, but it can still happen. Heat is more typically transferred through gases, however, by convection. When gases are heated they expand, and so become less dense. The less dense parts, being lighter, rise to the top. Similarly, the cooler, more dense parts, being heavier, move downward. This is the explanation for the well-known phenomenon, "Hot air rises and cold air sinks." In a closed container, convection currents are set up as the rising gas carries heat upwards and the cooler gas is brought closer to the heat source. The currents help distribute the heat throughout the container, and the whole process is driven by density differences. In contrast to conduction, where heat is transferred from molecule to molecule, in convection heat is transferred by *bulk flow*.

Students have probably already seen some examples of convection currents in gases. Smoke rises out of a chimney because of it, and steam rises from the spout of a tea kettle boiling water. There are also small holiday chimes that ring when a pinwheel, mounted over lit candles, turns because of convection. If your classroom has high ceilings, you can probably measure a few degrees of temperature difference between the cool air just above the floor and the warm air just below the ceiling.

Convection in liquids is perhaps less familiar, and a little harder to observe. One demonstration that is fairly effective is to fill a wide jar or beaker (having a diameter of at least 10 cm) with water and place it on a ring stand. Position a candle so that it is just beneath the jar, but is not centered under the jar. Instead the candle should be located somewhere along the circumference of the jar. Light the candle and then carefully place a drop of food coloring as close to the heat source as possible. You can do this with a disposable plastic pipette, which you can then simply leave in the jar. If you try to remove the pipette you will probably create currents in the water that will disperse the food coloring and interfere with the convection pattern you are trying to show.

When we're heating soup in a pot on the stove, we don't usually just wait until conduction and convection have done their things before we start eating the soup. Instead, we speed the process up by stirring the soup as it heats. When we do, the spoon helps move the warm liquid next to the walls of the pot away from them, bringing the cooler parts of the liquid to the walls where they, too, can be heated. This is called *forced* convection, as opposed to the natural, or *free* convection described above. In forced convection, we use some mechanical device to move the liquid, thereby moving the heat, too.

Heat Transfer by Radiation

The third type of heat transfer, radiation, is the transfer of heat energy through space by means of both infrared and visible light. Although it sounds rather abstract, we are all familiar with it because it is the way energy from the sun warms our planet. Warm objects radiate more heat than they absorb, and the radiation moves outward in all directions. Since it is a form of light, this energy transfer can be interrupted by putting a solid obstacle between the source and the object to be warmed: when you sit in the shade of a tree you no longer feel the radiant warmth of the sun on your skin. Furthermore, dark surfaces can absorb radiation while light-colored surfaces reflect radiated heat. Put sheets of black and white construction paper or pieces of black and white fabric side-by-side on a sunny windowsill, and after a minute or two students can feel the differences in their temperatures.

Simple Demonstrations of Conduction, Convection, and Radiation

Students can witness the three types of heat transfer by using a birthday candle poked into the bottom of an upside-down paper cup. Putting one end of a metal rod or spoon directly in the flame or just above it will allow the end of the metal to heat up. The heat will then spread by conduction to the fingers of the student holding it. You could even provide metal rods of various lengths and have students determine how long it takes the heat to travel out to their fingers for the different lengths. Short lengths of copper pipe are ideal, since copper has a very high conductivity.

If the students can sit very still without talking, they should be able to see smoke rising from the candle by free convection. This is easier to see if they briefly pinch the flame out, leaving the tip of the wick glowing -- and smoking. They can also try holding an aluminum foil pie pan (obtained from the grocery store) upside down about an inch above the flame. After a few moments they should see the smoke accumulate under the pie plate and then begin to escape out around its edges, where it will curl up toward the ceiling. Be sure to distinguish between the smoke and the heat, however. The smoke allows us to see the movement of the heated air, but it is not the heat itself. (A very smoky alternative to a birthday candle is a "bug coil," but this might set off a smoke detector alarm! If there is no breeze, this demonstration is well suited for outdoors.)

To see the effects of radiation, students will need to coat the tip of a toothpick with a bit of wax as it melts and runs down the side of the candle. If they let the wax harden for a few moments, they can then move the toothpick slowly toward the flame. They must, however, approach the flame from *below*, and they should not let the wax tip touch the flame. Rather, when the tip gets a centimeter or two from the flame, they should see the wax begin to melt. Since the tip is not touching the flame, the wax cannot be melting due to conduction. Since the tip is below the flame, it cannot be melting due to convection. Instead, the wax melts because of the heat radiated from the flame.

More Hot and Cold Cans

After students have learned about the three types of heat transfer, you can ask them to think back to the ways they tried to keep their cans warm and cold. Ask them to consider how they and their classmates took advantage of conduction, convection, and radiation, or, how they tried to eliminate them. Then, ask them to design new and improved devices so they can try, once again, to keep one can hot and one can cold.

You may want to let them bring in materials from home, but the same limitations as before should apply. Most of the successful warming devices we have seen involved insulating their cans with fabric, paper, or some other material. Insulation serves to prevent air from moving over the surfaces of the can, thereby eliminating or greatly reducing its ability to lose heat by convection. (We wear sweaters, fleece, and down or fiber filled coats in the winter for the same reason.) We have seen some students insulate their cans and run a tube from next to the can, through the insulation, and out to the mouth of a student, whose job it was to breathe warm air through the tube for the duration of the experiment. These students were trying to prevent heat loss by convection, but at the same time were using *forced* convection to carry heat to the can.

Other students have wrapped their cans in dark fabric or paper and set them on a sunny windowsill, taking advantage of radiation. One group of students, who had a large, athletic male among its members, had the young man run around the outside of the building for five minutes in order to work up a sweat. Then they had him lie on a table with their can held firmly in his armpit! Their method was a very effective example of warming by conduction!

As for cooling devices, students might simply place their cans on the concrete floor in a cool corner of the classroom, and take advantage of conduction and radiation. They can enhance this method of cooling, however, by fanning the can with a piece of paper for forced convection. If you allow them to use water, they might even wet their can and fan it dry. In this case they are letting evaporative cooling take place, which might merit further discussion.

After their second effort, have students compare the performances of their first and second heating and cooling methods. Again, line graphs of temperature versus time are very useful. By now students should also be able to use the terms conduction, convection, and radiation in describing their own and their classmates' devices.

Extensions

We encounter heating and cooling devices everyday in our homes, workplaces, and modes of transportation. Ask your students to give examples, and see if they can explain the roles conduction, convection, and radiation play in them. The following are examples that students might come up with, or ones you can share to get them started.

- The electronic devices in a desktop computer generate heat. You can feel the heat of the monitor rising out of the vents on its top surface. Processor units usually have small fans to help dissipate their heat by *forced* convection. If you remove the top of the processor unit, you should be able to see the fan at the back of the unit.
- Car engines generate a great deal of heat. The radiator, located just behind the grill, uses convection, conduction, and radiation to keep the engine cool. Water is circulated with a pump (forced convection) in pipes that run through the engine block, and heat from the engine is transferred by conduction to the water. The water is carried to the radiator, where it flows through much smaller pipes running past hundreds of small metal folds. Heat is transferred from the water to the metal folds, again by conduction. When the car is in motion, air moves over the surfaces of the radiator, and heat is carried away by convection. When the car is not moving, heat leaves mostly by radiation. All the folds of metal in the radiator create a great deal of surface area from which radiation can occur. Most cars also have a thermostatically controlled fan that will operate when the car is not moving but the engine is so hot that radiation alone will not be adequate for cooling.
- Similarly, a wood stove heats a room by conduction, convection, and radiation. The fire inside the stove heats the cast iron surfaces of the

stove, which then radiate their heat to the rest of the room. Convection currents are also set up when the heated air surrounding the stove rises to the ceiling, drawing the cooler air in the room to the stove where it, too, is then heated. The air next to the wood stove got heated in the first place by conduction.

- An electric or steam radiator works on the same principle: something hot inside the unit (water or wires carrying electricity) heats the metal surfaces. Radiators, whether they are found in a home or a car, typically are designed to have lots of surface area. This not only lets more room air come into direct contact with the hot radiator for conduction, but the large surface area also provides more radiant surface than would otherwise be available.
- Insulation put into the walls and roofs of buildings reduces heat loss by convection. Being thick, fluffy stuff, air cannot move easily through all the mixed up layers of fibers it is made of. Instead, the warm air in the house is trapped on one side of the insulation, and the cold air outside the house is kept on the other side.
- Similarly, clothing keeps us warm primarily by reducing heat loss due to convection, because it prevents the warmth of our bodies from being carried away, especially on a windy day. But clothing also prevents heat loss due to radiation. If you go outside on a cold, clear winter night, your mammalian skin radiates heat to the colder surroundings, and especially into outer space, where it is very cold indeed. Covering your skin with clothes not only provides insulation, but it also blocks and reflects back most of the heat your body radiates.

You can also ask students if they can think of examples of heating and cooling devices that occur in nature. Some examples are:

- Many animals lie down on cool, damp surfaces to help them lose heat by conduction. Others burrow down to where the ground is even cooler. Still others seek out cool water, another good heat conductor, to wade or swim in.
- A squirrel can hold its tail over its back as if it were a parasol, to block the sun's rays. Any shady area is the result of something getting in the way of the sun's light, which carries heat radiation with it. Animals that can't make their own seek out the shade of trees and plants, rocks, etc.
- Mammals that live in cold climates have thick, insulating fur. Many mammals that live where there are distinct seasons grow thicker fur during the winter and shed the excess insulating material when it is no longer needed during the summer.
- Jack rabbits living in the western desert areas have especially tall and narrow ears. They are full of blood vessels that run just beneath the skin. These blood vessels carry heat away from the interior of the rabbit's body and out to the ears, whose large surface areas can cool by radiation and convection. Elephants have exceptionally large ears that can serve as radiators as well. Elephants flap their ears frequently, presumably to add forced convection to their heat loss mechanisms.
- When their hives get too warm, bees use their wings to fan the hive interior, which is another example of cooling by forced convection.

Revised: February 21, 2001