Heat and Temperature

2. Thermal Equilibrium

You have on your table a black cup, a light bulb and a thermometer.

1. Imagine (don't do it yet) that some water is placed into the black cup (about 3/4 full), the thermometer is put into the water, and the bulb is turned on to illuminate the cup.

   A. Predict how the reading of the thermometer will change with time as the cup is illuminated. Make your prediction by sketching on the axes below how you think the temperature will change with time. In making your prediction, think about how the temperature will behave if the bulb is on to heat the cup for a very long time. (Note that the time axis extends to 150 minutes which is 2 1/2 hours.) Remember that a sketch need only be qualitative showing approximately the way the temperature changes as time goes on, i.e., as the black cup is heated by the bulb.

   B. Explain your thinking that led to your predicted graph.

   C. Discuss this with your partner and write down your thoughts. After some time to think about this, there will be a whole-group discussion for people to share their ideas. Write down some of the ideas expressed by your classmates.

Since the experiment to test your prediction takes some time, we will consider another prediction first, and then perform experiments to test both predictions at the same time.

HT-2.1
2. Imagine that you start with hot water (say, at 90°C, just below boiling) in the cup with the light bulb turned off. (You do not need the bulb for this experiment.)

A. Predict how the reading of the thermometer will change with time as the cup of hot water is left to itself. Once again, make your prediction by sketching on the axes below how you think the temperature will change with time. In making your prediction, again consider the temperature change assuming that the cup is allowed to cool for a very long time.

B. Explain your thinking.

C. Discuss this with your partner and write down their ideas if different from yours.

Now do both experiments at the same time (You need two black cups. Team up with another group and one group do Experiment #1 and the other do Experiment #2):

Experiment #1 - Fill one of the black cups with 100 mL of water and, before turning on the light bulb, record the temperature of the water. Turn on the bulb to illuminate the cup and, every 30 sec., record both the temperature on the thermometer and the total time elapsed from the beginning of the experiment. Record data for about 30-40 minutes and then ask your instructor to look at your data. Do not stop your experiment until your instructor tells you that it is OK to stop recording data.

Experiment #2 - Fill one of the black cups with 100 mL of hot water (close to boiling at the start) and record the initial temperature of the water. Every 30 sec., record both the temperature on the thermometer and the total time elapsed from the beginning of the experiment. Record data for about 30-40 minutes and then ask your instructor to look at your data. Do not stop your experiment until your instructor tells you that it is OK to stop recording data.
3. Share your data with your partner(s). If you did the heating experiment, share your data with the other half of your group that did the cooling experiment and vice versa. (Use the reverse side or a separate sheet of paper to write down the other group’s data.)

For each experiment, graph your data of temperature versus time.

A. Were your predictions confirmed by the experiments? If not, reexamine your ideas that led to your predictions and modify your thinking, as needed.

B. What is the interpretation of the slope of the graph of temperature versus time at any instant of time—i.e., what does the slope measure?

C. For both the heating and cooling experiments, the graph of temperature versus time should show different slopes at different times.

   i) Is the slope of the heating graph near the end of your experiment greater than, smaller than, or the same as the slope near the beginning? How do you interpret the difference between these slopes?

   ii) Is the slope of the cooling graph near the end of your experiment greater than, smaller than, or the same as the slope near the beginning? How do you interpret the difference between these slopes?

   iii) Imagine that you think of the time period during your heating or cooling experiment to be divided into three segments—beginning (first 1/3), intermediate (second 1/3) and end (third 1/3). In the intermediate time region of your graph (i.e., during the middle 1/3) describe what is happening to the slope. What do you think is causing the graph to behave this way during this time period?

D. If you continued the heating or cooling experiment for a much longer period of time, how do you think the reading of the thermometer will change with time, say after more than an hour? What evidence do you have?

E. In the cooling experiment, is the rate of temperature change greater when the cup was hot or when it became cooler? How can you tell?
4. While trying to make sense of the black cup heating experiment, a student offers the following analogy:

The flow of energy in the form of heat into (heating) or out of (cooling) the black cup can be considered to be analogous to filling a cylindrical bucket that has a hole in the bottom with water from a faucet as shown in the figure to the right. The constant input of water from the faucet represents the light bulb which provides constant energy input. Water pouring out from a hole in the bottom represents heat flow out of the heated cup. The temperature versus time graph in the heating experiment can be understood by thinking of filling this bucket.

A. (i) Assume that the hole at the bottom of the bucket is closed. With height of water on the vertical axis and time on the horizontal axis, sketch a graph of the height versus time (with the bottom hole closed). (A sketch need only be qualitative, showing approximately the way the height changes with time.)

(ii) Now imagine (again, starting with an empty bucket) that a small hole in the bucket is opened so that some water pours out from the bottom of the bucket while water is simultaneously being poured in from the faucet at the same constant rate as above. (Assume that the rate of water inflow from the faucet is greater than the outflow from the hole.) On the same sketch drawn above, sketch a graph of the height of water in the bucket versus time as the bucket fills with water. Label your sketches (i) and (ii) so as not to confuse them. Compare the slopes of your two sketches and explain your reasoning used in drawing the sketches the way you did.

B. Now assume that you want to drain a bucket that is already filled with water.

(i) With the faucet off, the water is allowed to drain through the open hole in the bottom. Sketch a graph of the height of water in the bucket versus time (with the faucet turned off).

(ii) Now imagine (again, starting with a bucket that already has water in it) that the faucet is turned on so that water pours out from the bottom of the bucket while water is simultaneously being poured in from the faucet at the same constant rate as above. (Assume this time that the rate of water inflow from the faucet is less than the outflow from the bottom hole, so that the bucket drains.) On the same sketch drawn in B(i), sketch a graph of the height of water in the bucket versus time as the water drains from the bucket. Label your sketches (i) and (ii) so as not to confuse them. Compare the slopes of your two sketches and explain your reasoning used in drawing the sketches the way you did.
C. Again, starting with a bucket that already has water in it, sketch a graph of the height of water in the bucket versus time if the water pours out of the hole at the same rate at which water pours in from the faucet.

![Graph of height vs. time](image)

5. A. Look back at your "Underpinnings" experiment involving height of liquid in a container vs. container shape. In that experiment, you were thinking about height vs. volume as a liquid fills a container. In the current experiment you are considering height vs. time as a liquid fills a container (the bucket). As long as the liquid flows into the bucket at a constant rate—which is assumed here—the volume increases linearly with time and the graphs of height vs. volume and height vs. time will have the same shape. With this in mind, answer this question:
   In parts 4A) and 4B) above, the graphs of height vs. time are all straight lines. Why?

B. Suppose that the graph of height vs. time for filling the bucket looked like that shown to the right rather than the straight line found in 4A) above. What would that suggest about the rate at which water is filling the bucket? Explain your thinking.

C. In the black can heating experiment, the temperature vs. time graph was not a straight line, but had the shape shown in the graph in 5B) above. In the student's "bucket analogy", the height of the water in the bucket is analogous to the water temperature in the black can heating experiment. What does the shape of the heating curve suggest about the rate at which thermal energy is entering the water in the can as it is heated? Explain your thinking.

6. After realizing that the heating curve is shaped like the curve in 5B) rather than a straight line, the student who created the bucket analogy modifies it. She now suggests the following:

*The heating experiment is analogous to filling a cylindrical bucket that has a hole in the bottom but also has holes leading up the sides of the bucket. As in the earlier version of the bucket analogy, the faucet represents the light bulb which provides constant energy input and water pouring out from the hole in the bottom of the bucket and the side holes represent heat flow out of the cup. The temperature versus time graph in the heating experiment can be understood by thinking of filling this hole-riddled bucket.*

HT-2.5
A. Let us examine this analogy a bit:

i) Consider the case when this hole-riddled bucket is nearly filled compared to the case when the bucket is nearly empty. In which case will the water flow out of the bucket through the holes be greater? Explain your thinking.

ii) As the lightbulb heats the black cup, is there any energy leaving the cup at the same time? How can you tell?

What aspect of the student's analogy deals with this? Explain.

iii) You noted earlier (in the cooling experiment—see 3E) that the rate of temperature change is greater when the black cup was hot than when it became cooler. What does this say about the rate at which energy leaves the cup as its temperature increases by heating from the lightbulb?

What aspect of the student's analogy deals with this? Explain.

iv) The net rate of change of energy input is the difference between the rate of energy going into the cup minus the rate at which energy is leaving. Assume that the energy entering the black cup is going in from the lightbulb at a constant rate. Combining that assumption with the conclusion from (iii) above, what can you conclude about the net rate of change of energy input to the cup and the consequent rate of temperature increase? Explain.
B. In section 3C above, you were asked several questions about the temperature versus time graph for the black cup heating experiment. These questions are restated below (with some modifications). Reconsider your answers to these questions with reference to the student analogy stated above.

(3C-i) How do you interpret the difference between the slope near the beginning of the heating curve and the slope near the end? [We know that the slope at the end is very different from the slope at the beginning. Use the student analogy to explain what this means.]

(3C-ii) What do you think is causing the graph to behave the way it does during the intermediate time period of your experiment?

C. Considering the analogy between the flow of energy in and out of the heated can and the flow of water in and out of the hole-filled bucket, what do you think causes the curve to level-out on the temperature versus time graph? (It might be helpful for you to refer back to question 4C.)

D. When a body radiates energy at the same rate that it absorbs energy, a physicist would say it is in thermal equilibrium. Consider the three regions of your graphs for the black can heating and cooling experiments (i.e., short time, intermediate time and long time after starting the experiment). In each experiment, when is the can in thermal equilibrium—near the beginning, near the middle or near the end of the experiment? Explain your thinking.