Improvements of Student Understanding of Heat and Temperature

Gina Quan
University of Washington Research Experience for Undergraduates 2011
and the Physics Education Group
Advisors: Paula Heron, Peter Shaffer, and Lillian McDermott

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Abstract

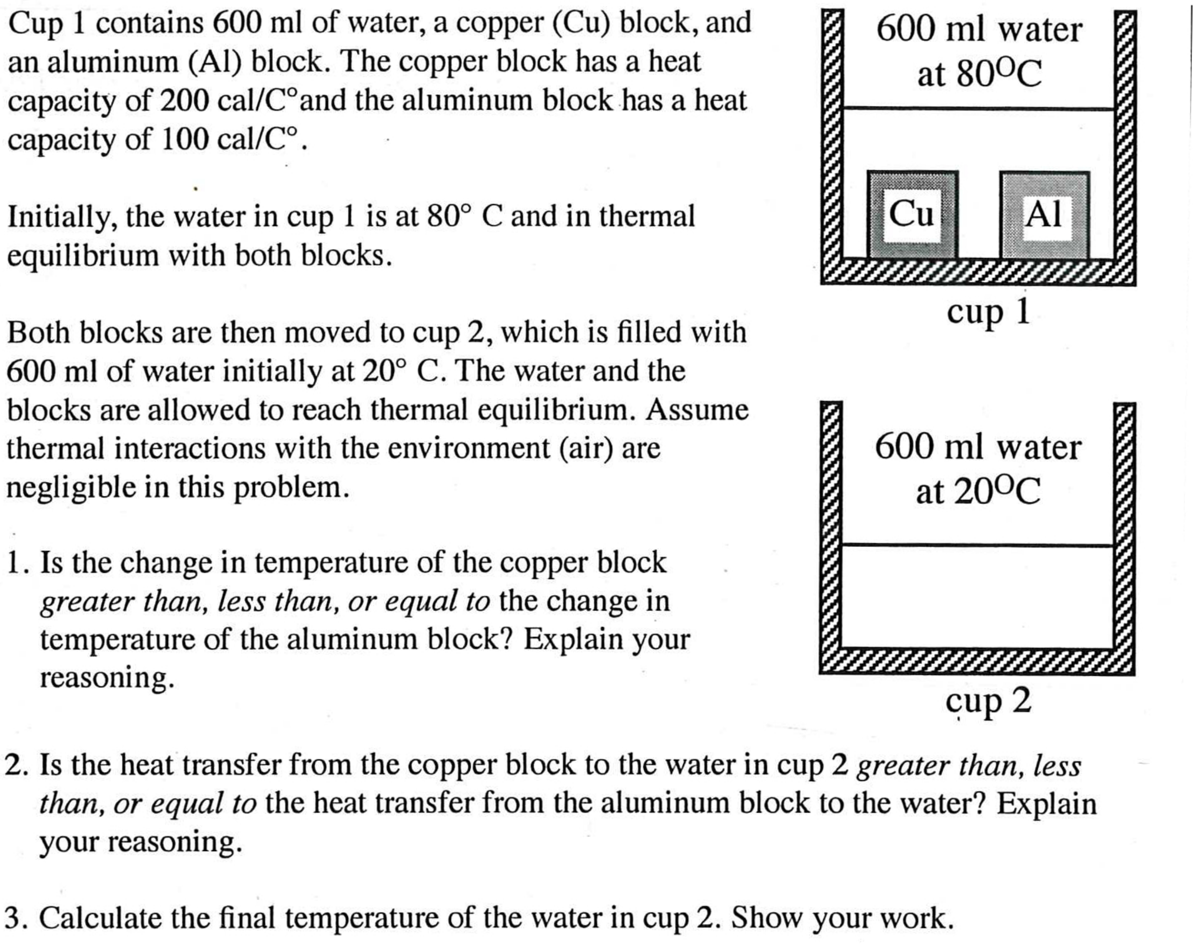
This paper reports on an investigation of student understanding of heat transfer. Extensive research has shown that students using the Physics by Inquiry[1] curriculum have demonstrated a solid understanding of topics and tasks directly covered within the module. However, since the design of this module, research on the learning and teaching of physics has revealed other difficulties not explicitly addressed in the curriculum. In this paper we will examine the effectiveness of the Heat and Temperature unit of the Physics by Inquiry curriculum and use specific student difficulties to suggest future modifications and areas of research.

I INTRODUCTION

Use of traditional lecture based instruction has proven to be an ineffective way for many students to gain a solid understanding of physical concepts. Research has shown that significant misconceptions in physics as well as a lack of scientific reasoning skills often persist after instruction. [3] Many physics education researchers attribute this deficiency in part to the failure of lectures to take into account students' existing beliefs and misconceptions[4].

The Physics Education Group (PEG) at the University of Washington has created a systematic method of developing and improving curriculum to help students build a coherent understanding of physical concepts. Student difficulties are identified in the analysis of pretests, past exams, and interviews. With this information, PEG continually refines curricula designed to improve student understanding of these difficulties. One such curriculum, Physics by Inquiry (PbI), is designed specifically for K-12 teachers. Physics by Inquiry consists of a self-paced module in which students design and conduct experiments and then build an understanding of the physics through observation. This curriculum teaches physics in a manner similar to the practice of real science; students work in small groups to answer questions through experimentation and application of knowledge cultivated earlier in the curriculum. At the end of each section, students talk through the material in a "check-out" with an instructor before moving on.

The Physics by Inquiry curriculum is implemented during PEG's NSF Summer Institute in Physics and Physical Science for Inservice K-12 Teachers. This year's Summer Institute consisted of 32 inservice K-12 teachers. The program ran from late June to late July for a total of five weeks. From 9:00AM to 11:45PM, teachers worked on a single morning topic throughout the institute. From 12:30PM to 3:45PM, teachers worked on two afternoon topics, each lasting half of the institute. The second afternoon topic, Heat and Temperature, will serve



Cup 1 contains 600 ml of water, a copper (Cu) block, and an aluminum (Al) block. The copper block has a heat capacity of 200 cal/C°and the aluminum block has a heat capacity of 100 cal/C°.

Initially, the water in cup 1 is at 80° C and in thermal equilibrium with both blocks.

Both blocks are then moved to cup 2, which is filled with 600 ml of water initially at 20° C. The water and the blocks are allowed to reach thermal equilibrium. Assume thermal interactions with the environment (air) are negligible in this problem.

1. Is the change in temperature of the copper block *greater than, less than, or equal to* the change in temperature of the aluminum block? Explain your reasoning.

2. Is the heat transfer from the copper block to the water in cup 2 *greater than, less than, or equal to* the heat transfer from the aluminum block to the water? Explain your reasoning.

3. Calculate the final temperature of the water in cup 2. Show your work.

Figure 1: The original calorimetry problem that was administered by Cochran (2005)[2].

as the basis for the research described in this paper.

II Description of Research

This research examines several specific difficulties that students have regarding thermodynamics. A considerable amount of research has been conducted on student understanding of heat and temperature. In 2001, Yeo and Zadnik developed a thermal concept inventory to probe student understanding of thermal concepts[4]. This instrument guided several of the problems that we administered. At the University of Washington, a 2005 doctoral thesis by Matthew Cochran [2] also found that students in the algebra-based physics course have difficulty distinguishing the quantities heat and temperature. This leads to difficulties understanding concepts such as thermal equilibrium and conservation of energy. Cochran also found that students with a weak understanding of heat and temperature also struggle with applying relevant equations[2].

This investigation explores if these student difficulties are present among K-12 teachers and the extent to which they persist after taking Physics by Inquiry. We began by administering a pretest on the second day of instruction to the 32 students (for this paper, we will refer to the K-12 teachers as students) in the Summer Institute. At the end of the unit the students were given an exam after they had completed 26 hours of the Heat and Temperature module. Exams were evaluated on their correctness of their responses as well as the quality of their reasoning.

We found that students in the Summer Institute did considerably better than the students in the algebra-based physics sequence. In this paper we will discuss two of the questions that were administered: one related to calorimetry and the other to thermal equilibrium and thermal conductivity. Both are specific concepts that were emphasized in the Summer Institute.

III Student Understanding of Calorimetry

In 2005, Cochran administered various calorimetry problems to students in several algebra-based physics classes at the University of Washington. At the end of instruction, two different classes were given the question in Figure 1 on an exam. In one version, the heat capacities were given in calories and in the other the heat capacities were given in joules.

To solve Part 1, one must understand that the blocks begin and end in thermal equilibrium so the change in temperature should be the same. To answer Part 2, students needed to recognize that the copper block has a greater heat capacity than the aluminum block so it should transfer more heat. In Part 3, to find the final temperature one must understand that the heat lost by the blocks is equal to the heat gained. By using the equation $Q = mc\Delta T$ for the blocks and the water one can find a final temperature of about 40 °C.

Cochran found that only 60% of students were able to answer both of the first two parts correctly, demonstrating a lack of understanding about thermal equilibrium and heat capacity. In Part 3, 15% of students who took the joule version were able to calculate the final temperature correctly while 30% of students who took the calorie version were were able to calculate the final temperature. He identified that the most common difficulty was misapplication of the equation $Q = mc\Delta T$[2]. To compare, we gave a similar problem on an exam in the Summer Institute.

III.A Curriculum Related to Calorimetry

As with the rest of the Physics by Inquiry curriculum, the Heat and Temperature module is far more conceptual than most traditional thermodynamics curricula. First, students build a foundational knowledge of heat and temperature through experimentation. These terms are operationally defined by students only after the need for the concepts are motivated.

Throughout the curriculum, students create a model for thermal interaction based on their observations, and the model is continuously revised. In one part of the model, they treat thermal interactions between two objects as successive transfers of heat between the two bodies until they reach the same temperature. An example of this method is in Figure 2 which shows the interaction of aluminum, nickel and water for the problem that will be discussed in III.B. In each step, one body transfers an amount of heat to another until equilibrium is reached. Although this method is somewhat tedious and may allow for calculation errors, the model makes explicit how the temperature of each body changes. Toward the end of the module, students arrive at the equation $Q = C\Delta T$.

III.B ANALYSIS OF POST TEST

As a post-test, we administered a problem (Figure 3) similar to Cochran's. For this question, we asked the students to use a table of successive heat transfers to arrive at the equilibrium temperature of the system. The first part was modified because students had spent some time working on mass and density in the module. The exam was open-book and open-note and students were given a table of specific heats and densities.

To solve Part A, one must first calculate the heat capacities. To find the heat capacities, one would multiply the specific heat, density and volume. To solve Part B one would create a table of heat transfers, exchanging different amounts of heat between objects until all objects are in thermal equilibrium. In Figure 2, a correct solution is found using successive heat transfers. A complete solution including student reasoning can be found in Appendix A.

Table 1: Comparison of student performance on calorimetry problem

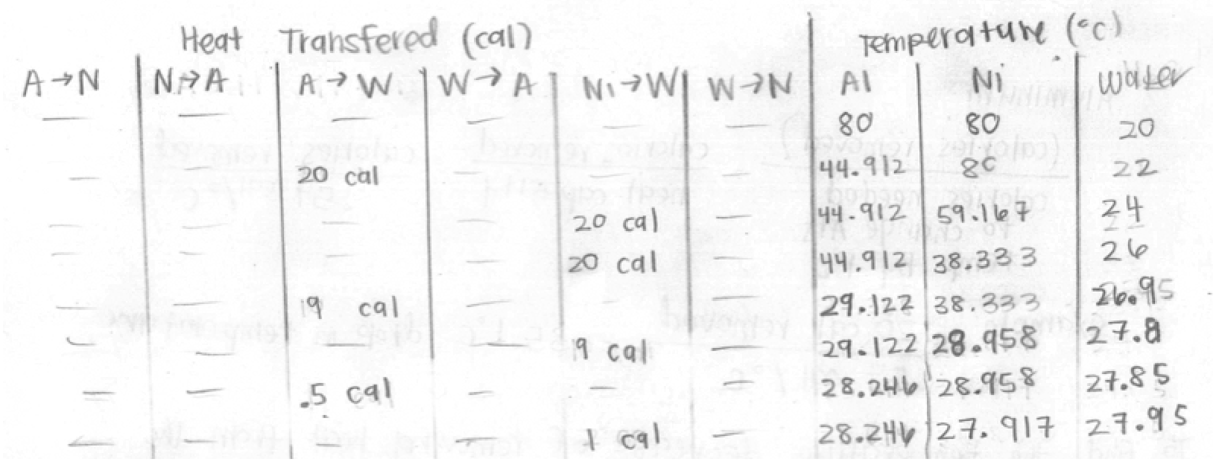
	Summer Institute (N=32)	UW 115-calorie (N=42)	UW 115-joule (N=69)
%Correct	56%	30%	15%

Students in the Summer Institute did well compared to the algebra-based course. 78% of students were able to calculate the heat capacities (students in the algebra-based course were not asked to do this part). Most of the incorrect responses for Part A were simple calculation errors as well as errors reading the table. In Part B, 56% of students correctly calculated the equilibrium temperature, along with 9% of students who calculated an equilibrium temperature consistent with incorrect heat capacities in Part A. This is significantly better than in the algebra-based course, which suggests that the Physics by Inquiry module considerably improved student ability to solve calorimetry problems. A comparison of these classes can be found in Table 1.

IV STUDENT UNDERSTANDING OF THERMAL EQUILIBRIUM

A common source of confusion among students is how two objects that feel different to the touch can be in thermal equilibrium. To probe this confusion, Cochran (2005) administered the following question to an algebra-based physics class post-lecture but before homework was assigned:

> "A block of wood and a block of aluminum, both of identical size, have been in a cooler with a bag of ice for a long time. The temperature of each block is measured with a thermometer. Is the temperature of the wood block greater than, less than, or equal to the temperature of the aluminum?"



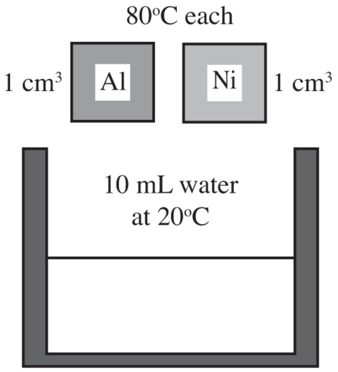
Heat Transfered (cal)						Temperature (°C)		
A→N	N→A	A→W	W→A	Ni→W	W→N	Al	Ni	Water
—	—	—	—	—	—	80	80	20
—	—	20 cal	—	—	—	44.912	80	22
—	—	—	—	20 cal	—	44.912	59.167	24
—	—	—	—	20 cal	—	44.912	38.333	26
—	—	19 cal	—	—	—	29.122	38.333	26.95
—	—	—	—	9 cal	—	29.122	28.958	27.8
—	—	.5 cal	—	—	—	28.246	28.958	27.85
—	—	—	—	1 cal	—	28.246	27.917	27.95

Figure 2: An example of how to use successive heat transfers to determine an equilibrium as in section III.A.

3. [40 points] An aluminum cube and a nickel cube each 1 cm on a side are each initially at 80°C.

   Both cubes are then moved into a cup, which is filled with 10 ml of water initially at 20°C. The water and the blocks are allowed to reach thermal equilibrium.

   Assume thermal interactions with the environment (air) are negligible in this problem.



A. [10 pts] Rank, from greatest to least, the heat capacities of the aluminum cube, the nickel cube, and the water. Explain your reasoning.

B. [15 pts] Use a table showing the results from successive transfers of heat until thermal equilibrium is reached between the water and the cubes to determine the final temperature of the system to the nearest degree. (An equation without an accompanying table will not receive full credit.) Explain your reasoning.

Figure 3: The new calorimetry problem as referenced in section III.B.

To answer this problem, students need to understand that if the blocks have been in the cooler for a long time, they are in thermal equilibrium and therefore must be the same temperature. Cochran found that only 45% of students answered correctly with 25% answering that the wood block had a higher temperature and 30% answering that the wood block had a lower temperature. Cochran noted that incorrect responses demonstrated a confusion between temperature, total heat transfer and conductivity[2]. We administered similar questions to the Summer Institute both early and later in instruction to see if the Physics by Inquiry module helped students understand this concept.

IV.A CURRICULUM RELATED TO THERMAL EQUILIBRIUM

The difference between temperature and the feeling of hot or cold is addressed in several parts in the curriculum. In Section 1 of the Physics by Inquiry curriculum, students explicitly reason that two objects that feel differently may have the same temperature. After measuring a block of wood and a block of aluminum at room temperature the module asks, "Does the feeling of hotness or coldness give a reliable indication of the temperature of the object? [1]. After students have found that all objects in a room have the same temperature as measured by the thermometer, the curriculum also defines thermal equilibrium: "In most thermal interactions between two objects, the temperature of the hotter one decreases and that of the colder one increases. Eventually the two interacting objects arrive at the same intermediate temperature."[1]. Two concepts emphasized in these exercises are that that objects will eventually reach equilibrium with their surroundings and that sense of touch is not a good indication of temperature. These observations form an empircal foundation for the introduction of heat transfer in the subsequent sections.

IV.B ANALYSIS OF FIRST SUMMER INSTITUTE RESEARCH TASK

In our first research task in the Summer Institute, we asked a modified verson of problem developed by Yeo and Zadnik[4]:

> "A student takes a metal ruler and a wooden ruler from his pencil case. He notices that the metal one feels colder than the wooden one. Explain why."

Students answered this problem on the second day of instruction after most had completed Section 1. All students had completed the exercise in which they measure the temperature of objects in a room with a thermometer. This question served as a post-test for the exercises in Section 1 as well as a pretest for the conductivity section later in the module.

Unsurprisingly, no student indicated that the temperature of the wooden ruler was warmer than the metal ruler.

Although most students answered correctly, their reasoning was not always correct. Most students, in their responses to this problem, attributed the observation that the metal ruler feels colder than the wooden ruler to some property of the materials. For example, 59% of students specifically mentioned the conductivity of the metal and 3% mentioned the specific heat of metal. Other responses did not refer to specific concepts but said metal "pulls more heat" or that "change in temp... is more easily felt" in metal.

We considered a correct reponse to include that the rulers are the same temperature because they are in thermal equilibrium with the room and that sense of touch does not indicate temperature. Of the responses, 31% of students explicitly stated that the rulers are in thermal equilibrium with the room and 59% stated that sense of touch is not a good indication of temperature. Other responses revealed misapplication or confusion of physics concepts. For example,

> "The surface area in contact with any given section of your skin is greater, more energy is transferred to the metal. It is a better conductor."

Overall, the responses were somewhat terse with incomplete reasoning. As is usual in the Summer Institute, reasoning improved dramatically after instruction. An example of a typical first and second research task can be found in Appendix B.

IV.C Analysis of Second Summer Institute Research Task

We then administered a similar question, also adapted from Yeo and Zadnik[4], for the final exam of the Institute to see if students' difficulties persisted after instruction. This problem was the third part of the Heat and Temperature section of the final.

> "A student takes a Popsicle out of a freezer, where he had placed it the day before. He notices that the Popsicle feels colder than the stick and concludes that the stick must be at a higher temperature than the Popsicle. Do you agree with him? Explain your reasoning."

Overall, students did well on this problem. While evaluating responses, we looked for three main criteria- the understanding that the popsicle and the stick are the same temperature, the understanding that sense of touch does not indicate temperature, and the clarity and reasoning of explanation. We found that 84% of the responses indicated that the popsicle and stick were in thermal equilibrium, 69% said that sense of touch does not indicate temperature and 56% used both in their reasoning. A typical response can be found in Appendix B.

As with the first research task, some students attributed the difference in feeling to conductivity, although to a much lesser extent on the second research task. They did so although thermal conductivity does not make an appearance in the curriculum until the last section. Only two students had started on the conductivity section by the end of the class. On the exams and throughout Physics by Inquiry, students are instructed to forget any outside knowledge they have and to base their answers only on observations they have made in class. This experience not only helps them in deepening their understanding of the concepts and process of science, it also gives them the background needed to guide their own students to an understanding of the ideas without skipping steps in the reasoning.

Although the responses were generally good, many students attributed the difference in sense of touch to a difference in specific heats. This could be due to the fact that nearly all students had just completed the section on specific heat. These types of responses are discussed in the next section.

IV.D Student Misconceptions of Specific Heat and Conductivity

A significant number of student responses used specific heat to account for the difference in feel of the popsicle and the stick. About 25% of students related the specific heat to the rate of heat transfer, demonstrating some confusion between specific heat capacity and thermal conductivity. For example,

> "The popsicle feels colder because it has a lower specific heat than the stick– meaning it takes less calories per gram to raise the temp by 1℃. It is absorbing heat from the hand faster than the stick and therefore feels colder. (The change in temp is greater for the popsicle than the stick for the same amount of time.)"

The rest of this response, as well as the other responses in this section can be found in Appendix C. It seems as though the student arrived at this response by realizing that the popsicle must be absorbing heat from the student at a faster rate than the wood, and assuming that the popsicle is more responsive to additions of heat. The popsicle's ability to absorb heat more readily could have been confused with having a heat capacity that is more responsive to additions of heat. This response demonstrates that the student understands that the rate of heat transfer is a factor in how we perceive hot and cold; however, there is a gap in understanding about the heat transfer.

In contrast, other students argued that the specific heat of the popsicle is greater than wood.

> "What the student may be noticing is a difference in specific heat between the ice and wood. Specific heat reflects how many calories a substance needs to raise 1g of it 1℃. It sounds like the wood needed fewer calories/gram to raise its temperature which is why it felt warm. (Less heat left his fingers in his thermal exchange). Ice probably felt colder because more heat is needed to raise its temp."

This response illustrates a difficulty understanding that the rate of heat transfer is a factor in how hot or cold an object feels. It seems as though the student was reasoning that if the wood feels warmer, it must have taken less heat from the student and would have reached equilibrium with the hand with less heat transferred. Here the student seems to be thinking in terms of a total quantity of heat rather than the rate of heat transfer.

These confusions regarding conductivity and specific heat suggest future directions of research. This and other ideas for the future will be discussed later in this paper.

IV.E STUDENT MISCONCEPTIONS OF SPECIFIC HEAT AND PHASES

Of the students who used specific heat to account for the difference in sense of touch, half treated the specific heat of the popsicle to be the same as that for liquid water. They argued that the popsicle had a greater specific heat than the stick.

> "The popsicle feels colder than the stick because the water in the popsicle requires more calories per gram to raise its temperature ($\frac{1cal}{g\,^{\circ}\mathrm{C}}$) than the wood does ($\frac{0.42cal}{g\,^{\circ}\mathrm{C}}$).

A table of specific heats was included in a table as an Appendix to the curriculum. Neither the table nor the curriculum state that the specific heat of liquid water is different than water ice. Interestingly, the specific heat of ice is about $\frac{0.5cal}{g\,^{\circ}\mathrm{C}}$, which is very nearly the specific heat of wood. Had we explicitly stated this on the exam, some students may have realized that a small difference in specific heat alone could not account for observation.

There are a few reasons why students may have used the specific heat of water to refer to the specific heat of ice. The table of specific heats given on the exam did not include ice, only water. Furthermore, in the module there is no mention that specific heat changes as materials change phase. There is a somewhat misleading portion of the curriculum that states that the specific heat of an object is nearly constant at all temperatures. It includes a table of the specific heat of water from the temperatures 0 °C to 100 °C and shows that it remains nearly constant (a copy of the table is included in Appendix D). Since students know that water freezes at 0 °C, they may have been assumed that water ice has the same specific heat as well. These confusions may give way to future areas of research and curriculum development.

V Future Research

There is not currently a pretest for the Conduction section of the Heat and Temperature module but one would be useful to further probe student understanding of conduction. This research has revealed that students' preconceptions regarding conduction of heat are complex and varied. In their responses they related conductivity to properties such as density, surface area and kinetic energy of the atoms. It would be interesting to see how and if other students are relating these properties to conductivity.

Because 25% of students demonstrated some confusion regarding specific heat capacity and conductivity, it may be useful to address this issue in the curriculum. A pretest or check-out question regarding the difference between heat capacity and conductivity could lead to interesting research. Though one may argue that students would have learned conductivity had they gotten to that section, one of the two students who worked through conductivity still attributed the feeling of coldness to specific heat. At the present time, it may be useful to emphasize in the module that heat capacity is not the only property that is a factor in how warm or cold an object will feel. This could be done in an experiment similar to the popsicle problem, in which students compare the specific heat and feel of two objects of similar specific heat. A problem like this could be a good transition into the conduction unit.

The confusion regarding specific heat of water and ice reveals a weakness in the curriculum to address how specific heat changes as phase changes. It may be worthwhile for future revisions to include experiments which measure the heat capacity of water ice to illustrate this concept. The specific heat of water ice should also be added to the Appendix in future versions.

VI Conclusion

The process of physics education research is ongoing. In the Heat and Temperature section of the Physics by Inquiry curriculum, it seems as though this year's Summer Institute students had resolved nearly all of the commonly identified misconceptions. However, the research that was conducted this year revealed other more complex difficulties that had not been previously known. It is the hope of physics education research that we can continue to identify these difficulties in order address them by helping students build a coherent understanding of the physics.

VI.A Acknowledgements

I would like to thank my research advisor Paula Heron as well as Peter Shaffer and Lillian McDermott for their endless guidance this summer. I also thank the rest of the members of PEG for their support, especially Donna Messina, Timothy Major, Brian Stephanik, Brittany Johnson and Nina Tosti. Finally, thank you to everyone involved in the REU-coordinators Subhadeep Gupta and Alejandro Garcia, Janine and Linda, as well as Megan, Emilie, Charlie, Arman and Micah. This project was made possible by the National Science Foundation.

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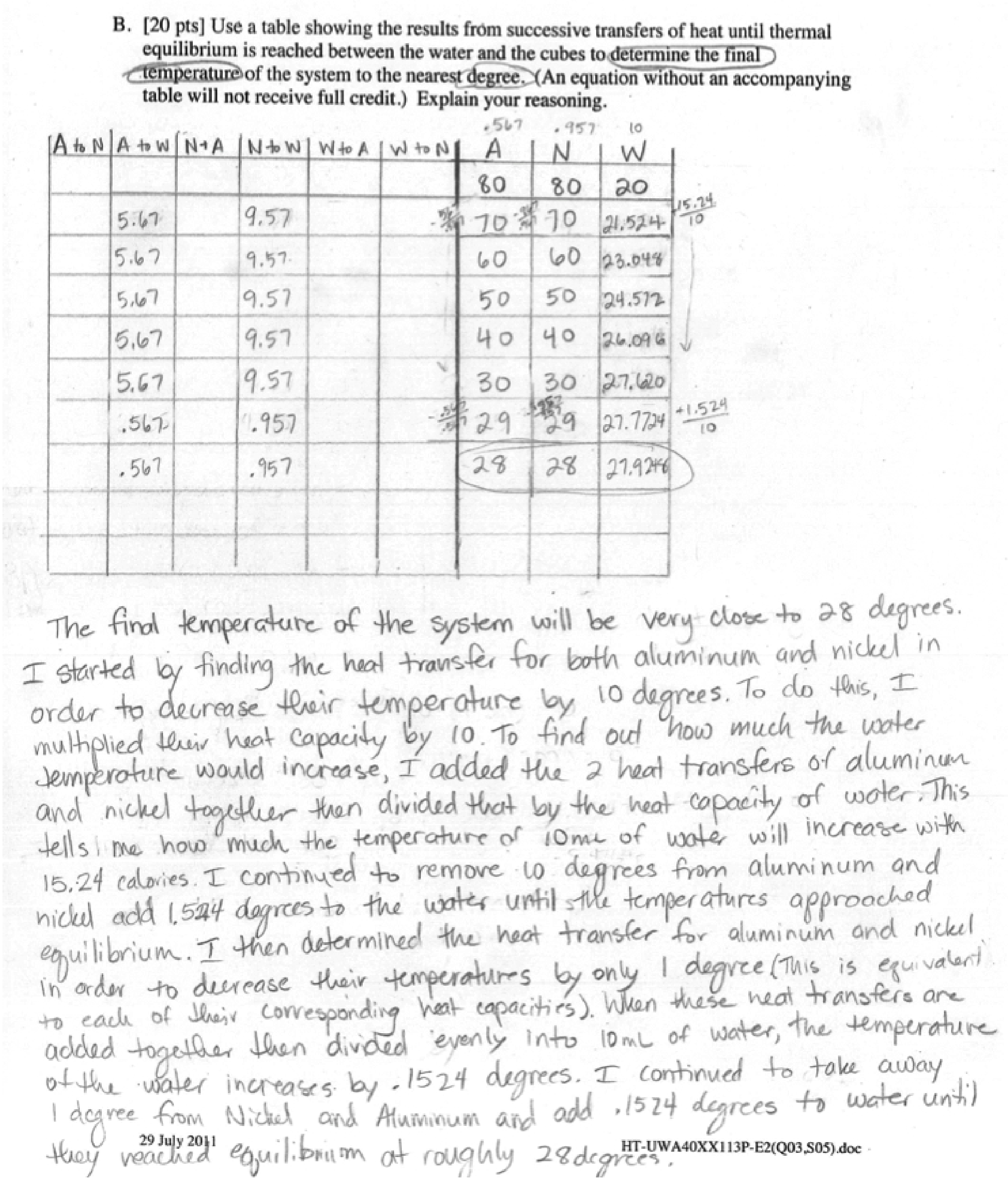
A Sample Student Response to Calorimetry Problem



B. [20 pts] Use a table showing the results from successive transfers of heat until thermal equilibrium is reached between the water and the cubes to determine the final temperature of the system to the nearest degree. (An equation without an accompanying table will not receive full credit.) Explain your reasoning.

.567 .957 10

A to N	A to W	N→A	N to W	W to A	W to N	A	N	W
						80	80	20
	5.67		9.57			70	70	21.524
	5.67		9.57			60	60	23.048
	5.67		9.57			50	50	24.572
	5.67		9.57			40	40	26.096
	5.67		9.57			30	30	27.620
	.567		.957			29	29	27.7724
	.567		.957			28	28	27.9246

$+\frac{15.24}{10}$

$+\frac{1.524}{10}$

The final temperature of the system will be very close to 28 degrees. I started by finding the heat transfer for both aluminum and nickel in order to decrease their temperature by 10 degrees. To do this, I multiplied their heat capacity by 10. To find out how much the water temperature would increase, I added the 2 heat transfers of aluminum and nickel together then divided that by the heat capacity of water. This tells me how much the temperature of 10mL of water will increase with 15.24 calories. I continued to remove 10 degrees from aluminum and nickel add 1.524 degrees to the water until the temperatures approached equilibrium. I then determined the heat transfer for aluminum and nickel in order to decrease their temperatures by only 1 degree (This is equivalent to each of their corresponding heat capacities). When these heat transfers are added together then divided evenly into 10mL of water, the temperature of the water increases by .1524 degrees. I continued to take away 1 degree from Nickel and Aluminum and add .1524 degrees to water until they reached equilibrium at roughly 28 degrees.

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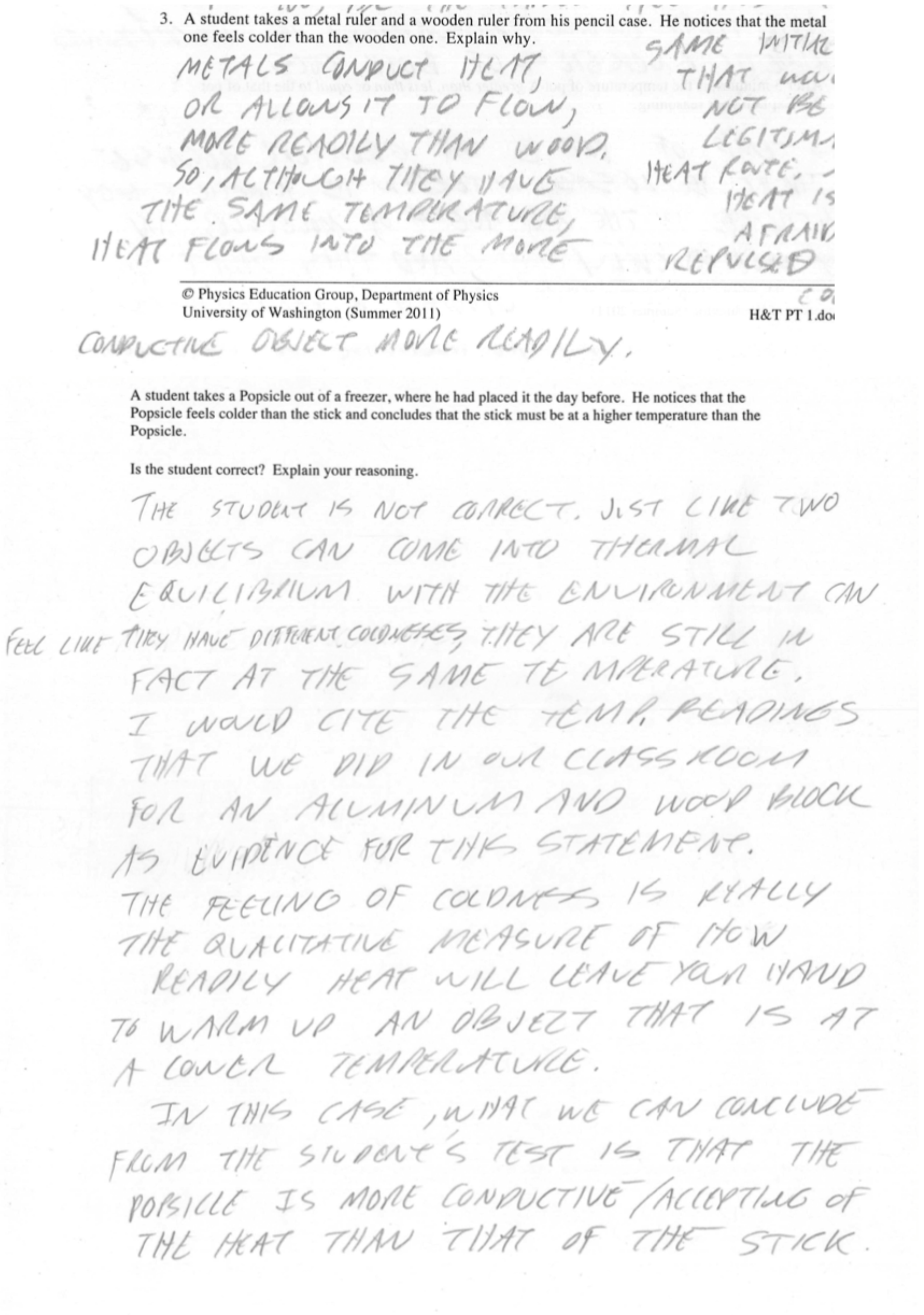
Figure 4: This is a typical student response to the calorimetry problem in section III.B.

B Student Response to Thermal Equilibrium Problem: First and Second Research Tasks



3. A student takes a metal ruler and a wooden ruler from his pencil case. He notices that the metal one feels colder than the wooden one. Explain why.

METALS CONDUCT HEAT, OR ALLOWS IT TO FLOW, MORE READILY THAN WOOD. SO, ALTHOUGH THEY HAVE THE SAME TEMPERATURE, HEAT FLOWS INTO THE MORE CONDUCTIVE OBJECT MORE READILY.

SAME INITIAL
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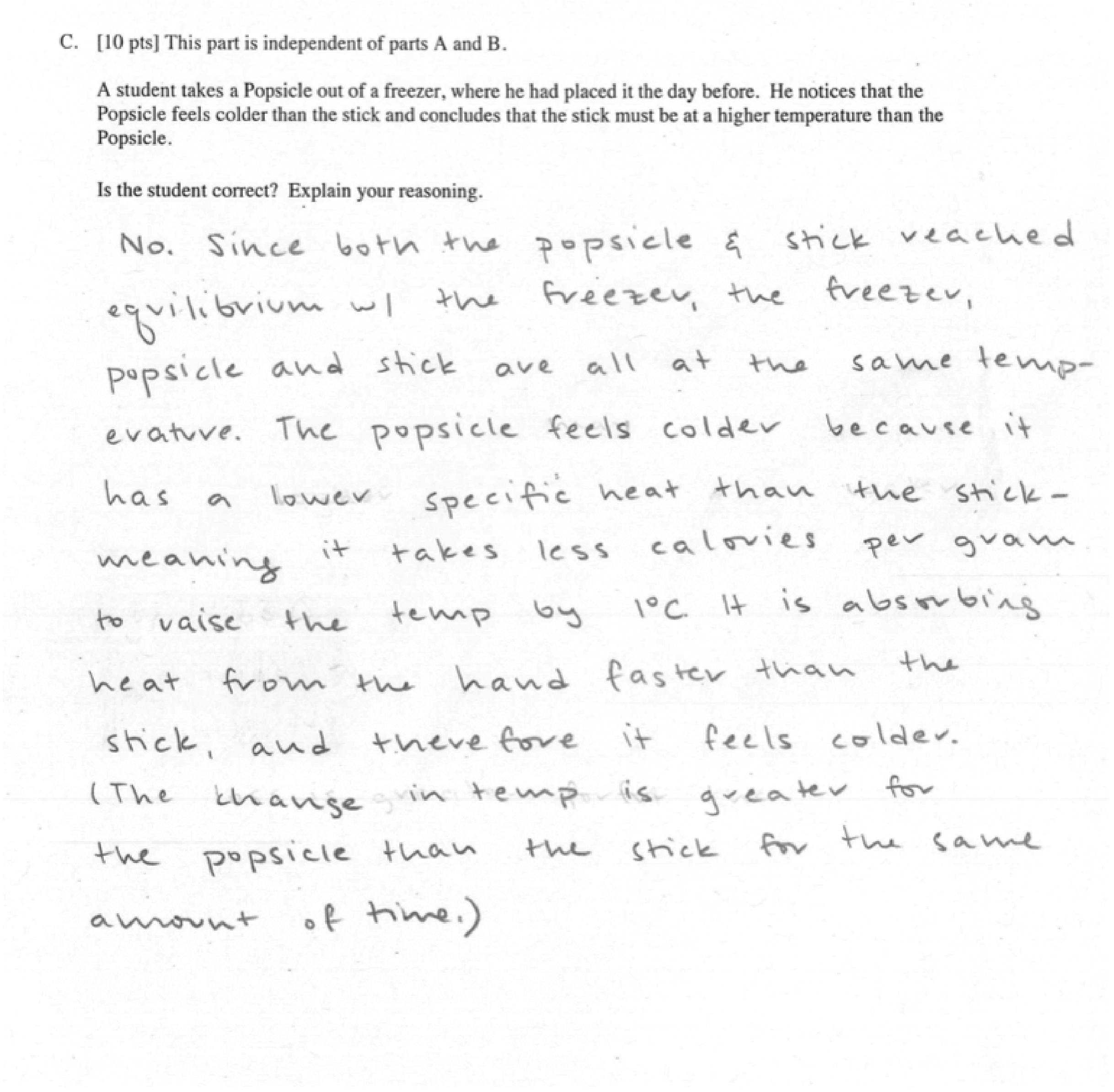
A student takes a Popsicle out of a freezer, where he had placed it the day before. He notices that the Popsicle feels colder than the stick and concludes that the stick must be at a higher temperature than the Popsicle.

Is the student correct? Explain your reasoning.

THE STUDENT IS NOT CORRECT. JUST LIKE TWO OBJECTS CAN COME INTO THERMAL EQUILIBRIUM WITH THE ENVIRONMENT CAN FEEL LIKE THEY HAVE DIFFERENT COLDNESSES, THEY ARE STILL IN FACT AT THE SAME TEMPERATURE. I WOULD CITE THE TEMP. READINGS THAT WE DID IN OUR CLASSROOM FOR AN ALUMINUM AND WOOD BLOCK AS EVIDENCE FOR THIS STATEMENT. THE FEELING OF COLDNESS IS REALLY THE QUALITATIVE MEASURE OF HOW READILY HEAT WILL LEAVE YOUR HAND TO WARM UP AN OBJECT THAT IS AT A LOWER TEMPERATURE. IN THIS CASE, WHAT WE CAN CONCLUDE FROM THE STUDENT'S TEST IS THAT THE POPSICLE IS MORE CONDUCTIVE/ACCEPTING OF THE HEAT THAN THAT OF THE STICK.

Figure 5: This is a typical set of one student's responses for the thermal equilibrium problems. The top response is from the first research task and the lower response is from the exam.

C Student Response to Thermal Equilibrium Problem Using Specific Heat



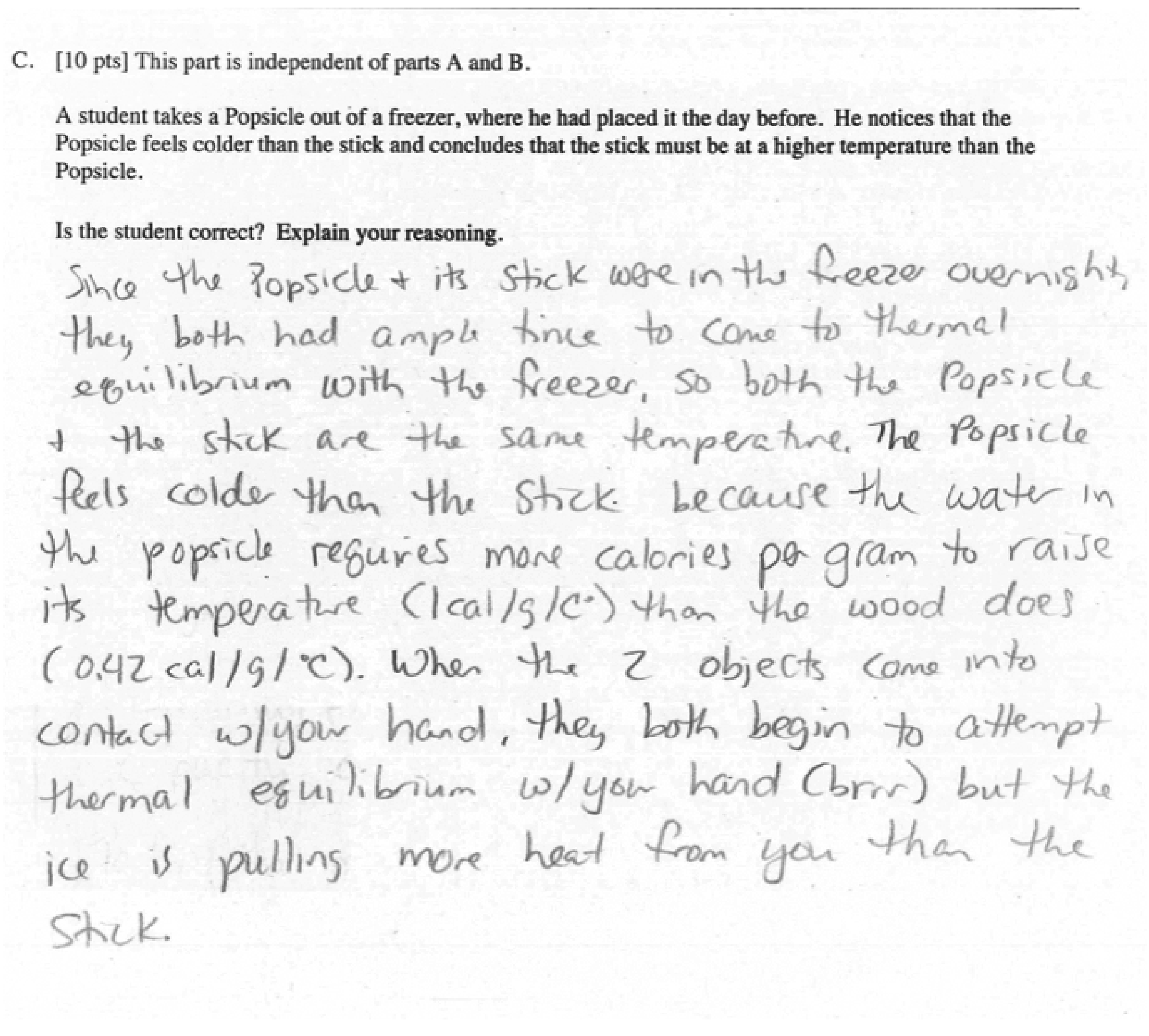
C. [10 pts] This part is independent of parts A and B.

A student takes a Popsicle out of a freezer, where he had placed it the day before. He notices that the Popsicle feels colder than the stick and concludes that the stick must be at a higher temperature than the Popsicle.

Is the student correct? Explain your reasoning.

No. Since both the popsicle & stick reached equilibrium w/ the freezer, the freezer, popsicle and stick are all at the same temperature. The popsicle feels colder because it has a lower specific heat than the stick - meaning it takes less calories per gram to raise the temp by 1°C. It is absorbing heat from the hand faster than the stick, and therefore it feels colder. (The change in temp is greater for the popsicle than the stick for the same amount of time.)

Figure 6: This is the full response of the specific heat example in section IV.D



C. [10 pts] This part is independent of parts A and B.

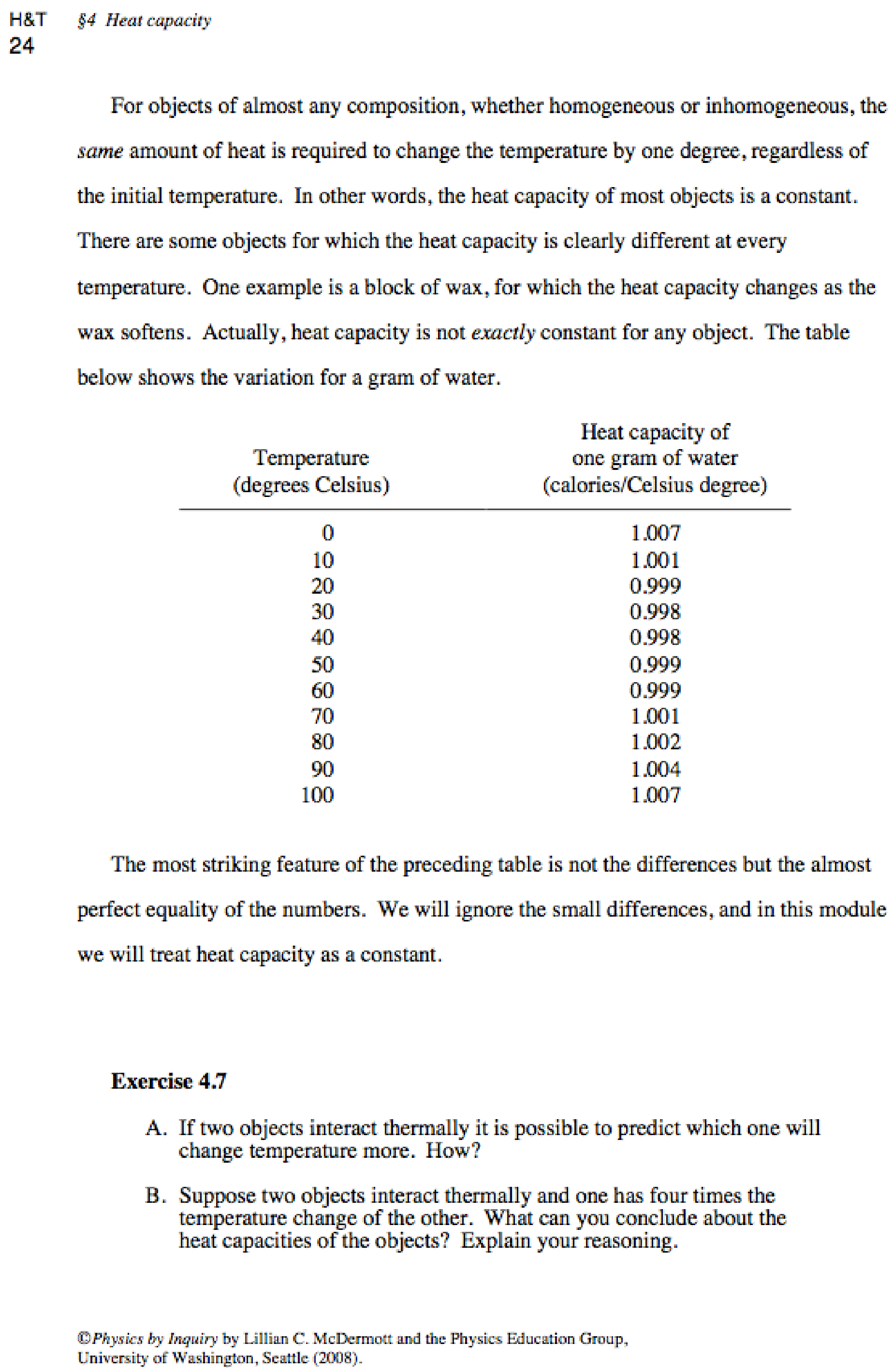
A student takes a Popsicle out of a freezer, where he had placed it the day before. He notices that the Popsicle feels colder than the stick and concludes that the stick must be at a higher temperature than the Popsicle.

Is the student correct? Explain your reasoning.

Since the Popsicle + its stick were in the freezer overnight, they both had ample time to come to thermal equilibrium with the freezer, so both the Popsicle + the stick are the same temperature. The Popsicle feels colder than the stick because the water in the popsicle requires more calories per gram to raise its temperature (1cal/g/C°) than the wood does (0.42 cal/g/°C). When the 2 objects come into contact w/your hand, they both begin to attempt thermal equilibrium w/your hand (brrr) but the ice is pulling more heat from you than the stick.

Figure 7: This is the full response of the specific heat example in section IV.D

D Specific Heat of Water



H&T 24 *§4 Heat capacity*

For objects of almost any composition, whether homogeneous or inhomogeneous, the *same* amount of heat is required to change the temperature by one degree, regardless of the initial temperature. In other words, the heat capacity of most objects is a constant. There are some objects for which the heat capacity is clearly different at every temperature. One example is a block of wax, for which the heat capacity changes as the wax softens. Actually, heat capacity is not *exactly* constant for any object. The table below shows the variation for a gram of water.

Temperature (degrees Celsius)	Heat capacity of one gram of water (calories/Celsius degree)
0	1.007
10	1.001
20	0.999
30	0.998
40	0.998
50	0.999
60	0.999
70	1.001
80	1.002
90	1.004
100	1.007

The most striking feature of the preceding table is not the differences but the almost perfect equality of the numbers. We will ignore the small differences, and in this module we will treat heat capacity as a constant.

Exercise 4.7

A. If two objects interact thermally it is possible to predict which one will change temperature more. How?

B. Suppose two objects interact thermally and one has four times the temperature change of the other. What can you conclude about the heat capacities of the objects? Explain your reasoning.

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Figure 8: This graph in the curriculum may have mislead students to believe that the specific heat of water is constant in any phase IV.E