AC 2011-407: THE USE OF INQUIRY-BASED ACTIVITIES TO REPAIR STUDENT MISCONCEPTIONS RELATED TO HEAT, ENERGY AND TEMPERATURE

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Introduction

There is broad recognition that meaningful learning requires that students master fundamental concepts. Understanding concepts and the connections among concepts is one of the primary distinctions between experts and novices (Bransford et al., 2000; Chi, 2006;). Conceptual understanding is also a prerequisite for students to transfer what they have learned in the classroom to new settings, something that is arguably among the most significant goals of an engineering education.

While there is little disagreement about the importance of conceptual learning, a wealth of evidence drawn from decades of research in the sciences (Lightman et al., 1993; Laws et al., 1999; Chi et al., 2005; Reiner et al., 2008) and a growing literature in engineering (Prince et al., 2010; Prince et al., in review; Krause et al., 2003; Steif et al., 2005; Miller et al., 2006; and Streveler et al., 2008) demonstrates that students generally enter our classrooms with misconceptions and that traditional instruction is often ineffective for promoting sizeable conceptual change. Addressing this problem requires a paradigm shift in teaching methods, from a paradigm of "teaching by telling" to one that more directly engages students at a conceptual level and lets them actively construct new meanings. Research, much of it in the sciences, has successfully demonstrated that a range of student centered instructional techniques can significantly improve students' conceptual learning gains (Hake, 1998; Laws et al., 1999; Reddish et al., 1997; and Mazur, 1997). There is a small but growing body of literature in engineering that supports similar conclusions (Prince et al., 2006, 2009).

Several factors explain why engineering education has not yet fully capitalized on the research, primarily in physics, for addressing student misconceptions. These factors include (1) the unfamiliarity of the relevant education literature to many engineering educators, (2) the lack of concept inventories with good estimates of internal consistency and validity that address core engineering areas and (3) the lack of tested educational materials in engineering similar to those that have been developed and tested in physics. However, significant progress is happening related to each of these issues. There is a widespread and rapidly growing awareness of the benefits of active-engagement methods in engineering education (Prince, 2004) and significant progress has been made in developing concept inventories for core engineering topics (Evans, 2003; Reed-Rhoads and Imbrie, 2007; Streveler et al., 2008). The lack of established educational materials specifically designed to repair important misconceptions in the core disciplines of engineering is arguably the predominant missing piece. This work seeks to help address that gap by developing inquiry-based activities to address four targeted student misconceptions in the area of heat transfer.

The paper begins by providing background information on conceptual change models and methods, illustrating both that misconceptions can be resistant to change while also identifying instructional approaches that have demonstrated success in other contexts. This is followed by a discussion of the research methodology, including a description of the sample demographics. Finally, results on the effectiveness of the developed inquiry-based activities for enhancing student learning are presented, along with a brief discussion of future work.

Background:

Conceptual Change Models and Methods

It is important to differentiate situations where learning is more easily acquired from robust misconceptions that are resistant to change. Chi (2008) distinguishes conceptual change from other situations based on students' preexisting knowledge. In those cases where students have either no prior knowledge or correct but incomplete prior knowledge, learning involves *adding* new information. However, in cases where students enter the classroom with significant misconceptions, learning requires *change*. Bransford et al. (2000) similarly stress the importance of understanding the state of students' preexisting knowledge when designing instruction. Significant research shows that conceptual change is difficult for a number of reasons. Ozdimir and Clark (2007) provide a good overview of conceptual change theories and Streveler et al. (2008) provide a targeted overview of conceptual learning in engineering.

While conceptual change is difficult, a number of approaches have shown promise for promoting conceptual learning relative to traditional instruction. Most of those approaches are active engagement methods and many are inquiry-based. Bernhard (2000) provides a good overview of the range of inquiry-based approaches that have been developed for physics education including Physics by Inquiry, Peer Instruction, Real Time Physics, Tools for Scientific thinking and workshop Physics. Prince and Felder (2006, 2007) provide extensive evidence that a variety of inquiry-based instructional methods are effective for promoting conceptual understanding as well as additional educational outcomes. The framework adopted for the activities presented in this study drew heavily on the Workshop Physics model, the defining elements of which (Laws et al., 1999) are shown in Table 1.

Table 1: Elements of Inquiry-Based Activity Modules (Laws *et al* 1999)

(a) Use peer instruction and collaborative work
(b) Use activity-based guided-inquiry curricular materials
(c) Use a learning cycle beginning with predictions
(d) Emphasize conceptual understanding
(e) Let the physical world be the authority
(f) Evaluate student understanding
(g) Make appropriate use of technology
(h) Begin with the specific and move to the general

Identifying Critical engineering Concepts and Misconceptions

Misconceptions related to heat, energy and temperature are widely recognized in the literature (Carlton, 2000; Jasien and Oberem, 2002; Thomas et al., 1995; Sozbilir, 2003). This study focuses on four targeted concept areas related to heat transfer that were identified from previous research as being both important and difficult for students to understand (Nottis et al., 2009; Prince et al., 2009; Streveler et al., 2003): (1) temperature vs. energy, (2) temperature vs. perceptions of hot and cold, (3) factors that affect the rate vs. amount of heat transferred and (4) the effect of surface properties on thermal radiation.

Developing Inquiry-Based Activity Modules for Targeted Misconceptions

Inquiry-based activities to address the targeted misconceptions were modeled after those developed by the Activity-Based Physics group (Laws et al., 1999; activities based physics webpage). This approach is similar to that proposed by others (Hausfather, 1992, Thomas et al., 1995) and has extensive empirical support (Laws et al., 1999; Thacker et al., 1994; Thomas et al., 1995) Letters in parentheses in the following description of the activities refer to the elements of Table 1 in order to demonstrate the consistency of the approach employed here with the methods described in Table 1. Students were put in teams (*a*) and asked to predict what would happen in a number of scenarios (*c*). A sample scenario is shown in Appendix 1. The students were then given physical experiments and/or computer simulations to test their predictions (*b, e, g*), after which they were asked to discuss how their thinking had changed if their predictions did not match reality. All the questions were conceptual in nature (*d, f*), using technology where appropriate (*g*). At the end of the specific activities, students were asked to step back and generalize what they had learned from the specific experiments and in some cases were asked to extend that knowledge to a novel application in order to determine if the learning was transferable to a new situation (*h*).

Methodology

This exploratory study examined the effect of 8 inquiry-based activities for improving students' conceptual understanding in 4 targeted concept areas using the newly developed Heat and Energy Concept Inventory (HECI). The instrument was designed specifically to assess these specific concept areas and has demonstrated acceptable levels of internal consistency reliability and content validity (Prince et al., 2011).

A quasi-experimental design with intact groups was used to assess learning gains. The two groups were a test group that were given the activities and a control group that was not. Participants completed a computerized version of the HECI prior to and after instruction. Detailed instructions were provided as a cover page to both the faculty administering the concept inventory and students completing it. The instructions specified that the pre-test was to be conducted within the first two weeks of the semester and that the post-test should be completed within the last two weeks of instruction. Test conditions were specified to standardize the students' experience. They included that the concept inventory should be completed individually within one hour without the assistance of any reference materials. Instructors were encouraged to provide some modest grade incentive, such as awarding of bonus points, for students to make a serious effort to answer the questions completely. Instructors were given the flexibility to administer the instrument either in or out of a regularly scheduled class period. Students were told that none of the questions on the instrument were purposely designed to mislead them and were instructed to make their best effort to answer all questions. Measurements for the control group assessed pre/post changes on the HECI under normal conditions, that is, without the use of the activities. Student learning gains for this sample were compared to gains found for a test sample of students who experienced the activities in their heat transfer course.

Descriptive statistics examined changes in knowledge, as measured by the mean scores of participants on the entire concept inventory as well as in each conceptual area sub-test. Independent t-tests were used to examine the differences between pre and post-test scores of the two groups (e.g., difference in pre-test scores of control and test groups). Dependent t-tests were used to examine pre-post learning differences for both the control group without activities and for the test group with activities. Normalized gains were also used to compare the groups. In addition, effect sizes, using Cohen's *d*, were calculated to show the magnitude of the difference between the means of each group. The appropriate measure of effect size for t-tests is Cohen's *d* (Cronk, 2010).

Demographics

The HECI was administered as a pre-test of existing knowledge to a control group of 373 undergraduate engineering students at ten different universities or colleges. The selection of schools included geographically diverse private and public institutions from across the United States, ranging in total enrollment from approximately 2,000 to 40,000 students. The concept inventory was used in 11 course offerings, two of which were offered at the same institution in two different semesters. Of the 373 respondents, 344 completed the concept inventory again after instruction in a heat transfer course.

The test group consisted of a sample of 129 students at 4 undergraduate institutions. The HECI was administered as a pre-test of existing knowledge to this group. Of the 129 respondents, 116 completed the concept inventory again after instruction that included administration of the inquiry-based activities. Demographic information for both student samples is shown in Table 2. An example inquiry-based activity is shown in Appendix 1. Sample instructions to faculty are shown in Appendix 2. As described earlier, each activity was designed to incorporate each of the elements of inquiry-based activities as defined by Table 1. There were 8 activities tested in this study, two targeting each of the four concept areas of the HECI. Students at each institution used all of the activities.

Table 2: Demographics of Student Samples for both Control and Test Groups

Control Group (No Activities)	*Test Group (Activities)*
Totals: *N = 373 (pre), 344 (post)*	*N=129 (pre), 116(post)*
Gender: *73.4% Male, 26.6% Female*	*76.0% Males, 24.0% Female*
Ethnicity: *80.9% white, 9.8% Pacific Islander, 2.9% African American, 2.4% Hispanic*	*Ethnicity:* *83.7% white, 7.0% Pacific Islander, 0.8% African American, 3.1% Hispanic, 0.8% Multiracial, 4.7% other*
Academic Major: *39.5% chemical engineering, 47.4% mechanical engineering, 3.7% civil engineering, 0.3% environmental engineering, 9.2% "other"*	*Academic Major:* *51.2% chemical engineering, 36.4% mechanical engineering, 2.3% civil engineering, 10.1% "other"*
Class Year *30.2% Seniors, 60.5% juniors, 7.9% sophomores, 0.3% graduate students*	*Class Year* *14.0% Seniors, 65.9% juniors, 20.2% sophomores*

Results

An independent t-test showed no significant difference between the test group using the inquiry-based activities and the control group on the total pre-test scores, (t(487) = 1.454, p>0.05). Paired samples t-tests showed that there was a statistically significant improvement from pre- to post-test scores for both the test and the control groups. A summary of the results as assessed by pre/post measurements using the HECI for both the control and test groups is shown in Table 3. As can be seen from the table, while student learning gains in the control group were statistically significant, they were modest (t(336) = -7.737, p<0.01, d=0.42). The magnitude of the effect size suggests a moderate effect. By contrast, the significant improvement with inquiry-based activities was larger (mean score of 46.1% on the pre-test to a mean score of 70.1% on the post-test), (t(89) = -13.39, p<0.01, d=1.41) and the effect size indicates a very large effect. Fraenkel and Wallen (Fraenkel and Wallen, 2009) have recommended that an effect size of 0.50 or greater should be interpreted "as important" (p. 244).

Table 3. Mean Pre/Post Performance Data by Content Area, With and Without Activities

Content Area	Mean Score, Control (no activities)		Mean Score, Test (w/ activities)	
	Pre-Test N = 373	Post-Test N = 344	Pre-Test N=116	Post-Test N=103
Temperature vs. Energy	52.8%	54.7%*	34.8%	68.5%**
Temperature vs. Perceptions of Hot or Cold	61.2%	69.4%**	59.1%	77.4%**
Rate vs. Amount	36.9%	42.6%**	51.7%	85.9%**
Thermal Radiation	44.4%	49.5%**	39.5%	68.7%**
Overall	**49.2%**	**54.5%****	**46.6%**	**70.1%****

* Statistically significant at the p < 0.05 level.

** Statistically significant at the p < 0.01 level.

One conventional measurement used in much of the conceptual change studies involving physics students is the normalized gain, defined as the improvement in student scores normalized by the possible gain. For example, the normalized gain for students in the control group is 10.4%, calculated by looking at the measured gain of 5.3% (54.5%-49.2%) divided by the total possible gain of 50.8% (100%-49.2%). This can be compared to a normalized gain of 44% with activities. A chart comparing normalized gains on the instrument as a whole as well as for each of the sub-categories of the HECI is shown in Figure 1. The data shows that the activities improved student learning gains in each of the four targeted concept areas as well as for the overall. These gains are significant, both statistically and in absolute terms.

Finally, an independent t-test was used to examine the differences in post-test scores between the control and the test (inquiry activity) groups. Effect sizes were also calculated to characterize the magnitude of the difference. The test group scored significantly higher than the control group on the post-test (t=-8.33, p<0.01, d=0.88). The magnitude of the effect size as measured by Cohen's d indicates there was a strong effect.

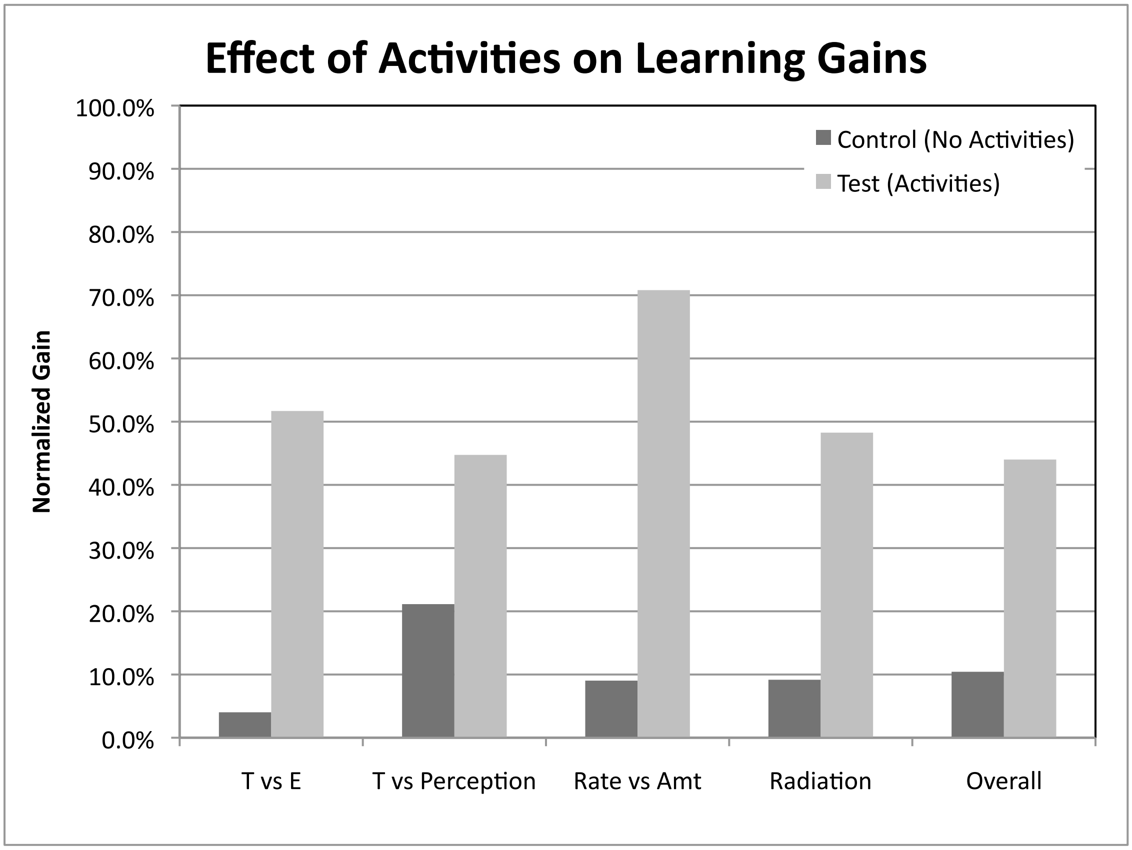

Figure 1. Effect of Activities on Learning Gains

Conclusions and Future Work

This study builds on earlier research in a number of ways. Consistent with a large body of literature, the data from the control group demonstrates that students have significant misconceptions about heat, energy and temperature and that these misconceptions are frequently robust or resistant to change through conventional instruction. The modest learning gains found for the control group support that finding. At the same time and again consistent with a large body of literature in the sciences, it has been shown that the use of inquiry-based activities can significantly increase student performance on measures of conceptual understanding, even in those cases that are resistant to change through conventional instruction. Again, the significantly improved student performance, both in the aggregate and for each of the targeted concept areas of the HECI, supports this assertion. Taken as a whole, this work contributes to our understanding by adding to what is at present a small data-base of the effectiveness of such activities with undergraduate engineering students.

While these results are very encouraging, there is a need for significant future analysis. We are in the process of examining two additional features of student learning gains, long-term retention and transfer. In future work, we will examine how effectively the activities promote conceptual learning gains immediately after their completion compared to student performance on the concept questions several weeks after the activity. In addition, 25% of the concept inventory questions reflect the situations found directly in the inquiry-based activities. Because of that parallel construction, it would be important to examine and contrast student performance on questions directly related to the activity from those that asked students to apply their understanding of the concept to new situations. This latter will provide additional information about the effectiveness of the activities for promoting transfer, a key educational outcome and one that is often difficult to achieve. Finally, it would be beneficial to have additional measures of students' conceptual learning, drawn from additional venues such as concept maps or semi-structured student interviews.

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Appendix 1: Sample Activity

Inquiry-Based Activity 1: Cooling Beverages with Crushed Vs. Block Ice

Introduction:

In this activity you will be adding the same mass of ice, either as a solid block of ice or as crushed ice, to a beaker of water and recording the rate and amount of cooling provided by each option. You are asked to make predictions and compare those predictions to what happens, along with answering some follow-up questions.

Materials:

2 1-liter beakers
2 magnetic stirrers with stir bars for mixing contents of the 1-liter beakers
Crushed ice (approximately 1 liter)
Small trays on which to weigh out ice
Scale to weigh approximately 40 grams of ice.
Food coloring (optional; if used, try to match to colors of data logging software)
Computer with data logging software (such as Vernier Labpro) to record temp. vs. time
2 temperature sensors specific to the data logging software being used

Note: The experiment can be run with thermometers and watches if more advanced data acquisition equipment is not available. Students can simply record temperature vs. time manually for each system.

Directions:

1. Predict which system will cool the ice to a lower temperature and which will cool the beverage more quickly. Make and record these predictions below, without talking to your lab partners or classmates.

   A. Which option will cool the water to a *lower* temperature? Why? (Answer in space below)

   B. Which option, if either, will cool the water more *quickly?* Why? (Answer in space below)

2. Place 1 beaker on each of the magnetic stirrers and place a magnetic stir bar in each beaker. Set each stirrer so that each provides the same degree of agitation.
3. From a common container, pour approximately 600 ml. of room temperature water into each of the beakers and turn the stirrers on to the same speed. It is important to use a common container to ensure both beakers have the same initial temperature. If using food coloring, add a few drops to each beaker.
4. Insert the temperature sensors and either start the computer acquisition program to record the initial beaker temperatures or manually record the initial temperatures.
5. Weigh approximately 40 grams of crushed ice into each of two small trays. Make sure both trays contain the same mass of ice. Take one of the ice samples and form it into a tight “snowball”. Minimize any water (melted ice) in your ice samples by using fresh ice.
6. Add the loose crushed ice to one of the agitated water beakers and the “snowball” to the other agitated beaker. Immediately begin recording temperature as a function of time with the data

acquisition equipment (e.g. Vernier Labpro) until the temperatures of both beakers have stopped changing. Note the initial rate of cooling and the final temperature for each system.

Analysis:

Please answer each of the questions below. This analysis may be conducted outside of class or laboratory for homework. While you should submit individual solutions, you are strongly encouraged to arrive at answers through discussion with laboratory partners or classmates. Remember to put your name or identifying student number on each page of your response.

1. Compare your initial predictions to what actually happened. Were your predictions correct?

2. If the experimental results do not match your initial predictions, come up with a new explanation of the results. In your explanations, you should pay particular attention to *why* your original predictions were not correct and how you had to revise your thinking to explain what happened.

   You should discuss your answers with at least 2 other students and agree on what happened and why.

3. Again working with others, write out the mathematical equations which should govern (1) the *rate* and (2) the *amount* of cooling provided by the ice. If necessary, consult your textbook or other sources. Compare your experimental data to your mathematical models and make sure that your model and results agree or that you can explain any discrepancies.

4. Again working with others, answer the following related questions:

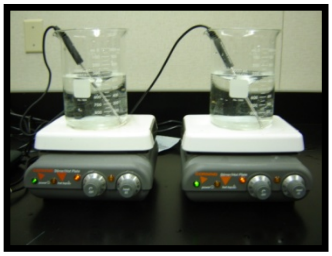
   a. Do factors which increase the rate of heat transfer always increase the amount of heat transfer too?

   b. Can we generalize the answer to that question to other processes such as mass transfer? For example, do factors which increase the *rate* at which a sugar cube dissolves in water (such as stirring) also increase the final amount of sugar dissolved in water at equilibrium?

5. What, if anything, did you learn in this activity?

Appendix 2. **Laboratory Set-Up for Packet 1**

Activity 1: Cooling Beverages with Ice



Laboratory Set-up

This experiment was done at Bucknell using Vernier Labpro software to collect and display temperature vs. time data. The same data can be collected with thermocouples or thermometers and a timepiece, and then plotted. A photo of the set-up is shown to the right and various Labpro screen displays are shown below as part of the technical analysis.

Note: *In some experiments, ice melt trapped in the snow ball caused the packed ice to provide less cooling (since the same mass of ice-cold water does not provide the same cooling as ice due to the heat of fusion). Be sure to use fresh chipped ice or to make efforts to avoid trapping ice melt (liquid water) in your samples.*