2006-1379: USING INQUIRY-BASED ACTIVITIES TO PROMOTE UNDERSTANDING OF CRITICAL ENGINEERING CONCEPTS

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Using Inquiry-Based Activities to Promote Understanding of Critical Engineering Concepts

Abstract

This NSF funded (DUE 0442234) study examines the use of inquiry-based teaching to promote understanding of critical engineering concepts. Significant research shows that students often enter the classroom with tightly held misconceptions about the physical world that are not effectively addressed through traditional teaching. As a result, students are frequently able to solve problems that have been explicitly taught, but are unable to apply course concepts to solve real problems not seen in class. Failure to grasp prerequisite concepts also leaves students poorly prepared for more advanced study.

Students' conceptual understanding can be dramatically enhanced, however, through a paradigm shift in teaching that incorporates inquiry-based methods. This is an inductive and collaborative teaching method where student teams are first introduced to specific, thought-provoking exercises. Students are placed in carefully designed situations where reality, rather than the professor, can dispute their preconceptions. The effectiveness of this approach has been extensively documented using thousands of undergraduate physics students. It has also been shown that emphasizing conceptual learning does not come at the expense of covering content or developing students' problem-solving ability. As of yet, however, inquiry-based activities have not been systematically developed for engineering education.

This work is a step towards filling that gap. In the initial phase of the project, the work targets one student misconception relating to heat transfer. The specific misconception addressed is the differentiation between factors impacting the *rate* of heat transfer versus those impacting the *amount* of heat transfer. Educational materials to address student misconceptions in these areas have been developed and tested.

The effectiveness of the prototype materials was assessed using concept inventories. Concept inventories are reliable and valid multiple choice assessment tools specifically designed to identify common misconceptions. Members of the research team that developed a relevant concept inventory for thermal and transport science are involved as collaborators on the current project.

This paper shares the results from the first year of testing with inquiry-based lessons. The preliminary results have been quite positive. Concept inventories were used as pre- and post-course measures of student understanding in order to document actual learning gains. This was done for two distinct course offerings, one taught normally and one taught using inquiry-based activities. As a result, we have documented learning gains with and without the use of inquiry-based activities. While normal instruction did little to alter student misconceptions in the targeted areas, inquiry-based methods were found to be significantly more effective. Ongoing work will refine the existing activities, as well as test the effectiveness of new activities for thermodynamics courses designed to reduce misconceptions about entropy.

Introduction

Recent research emphasizes the critical importance of conceptual learning. Indeed, of three key findings in the National Research Council's study on how people learn [1], the first finding is the need to draw out and engage student preconceptions and the second finding highlights the need for students to understand facts and ideas in the context of a conceptual framework. In short, meaningful learning in science and engineering requires that students master fundamental *concepts* rather than simply memorizing facts and formulas [2, 3]. All science and engineering curricula are designed with the expectation that students master prerequisite concepts which then provide the foundation for further study. Without a solid understanding of important concepts, students simply continue to incorporate vague ideas into an uncertain knowledge base. As a result, students might be able to solve problems that have been explicitly taught, but are unable to apply course concepts meaningfully to solve real problems not seen in class. Failure to master important prerequisite concepts also leaves students ill-prepared for more advanced study.

Teachers are often taken aback to learn the extent to which students in their courses fail to grasp important concepts [2, 4]. What is surprising is the level of conceptual misunderstanding present even among students who solve test problems correctly. For example, students in a physics course might correctly calculate the terminal velocity of a falling object using the appropriate formula, but still predict (if asked) that a 10 lb. metal weight will fall twice as fast as a 5 lb. weight. That is, simply learning the correct equations does not necessarily overcome the fundamental misconceptions that students bring to the classroom and which inhibit their ability to master more advanced topics.

Equally disturbing is the literature which shows that traditional educational methods are not very effective for addressing fundamental student misconceptions about the physical world [2, 5, 6]. Research involving thousands of first year physics students, for example, demonstrates that traditional teaching methods produce only marginal improvement in student's conceptual understanding of basic physics concepts [5, 6]. Even more surprising are those studies which demonstrate that in some cases traditional instruction actually results in a *decreased* understanding of concepts that have been taught [2]. Obviously, addressing student misconceptions involves more than simply telling them the right information. If that were the case, traditional instruction would easily improve the situation.

The prevalence and persistence of student misconceptions is not due simply to inattentive or unconscientious teaching. Instead, it requires a paradigm shift in teaching methods from one of "telling" to one in which students are forced to directly confront their misconceptions. Most engineering faculty are only now becoming aware of the literature that highlights this problem and which details possible solutions.

The Research Base on Which the Project Builds

It is now recognized that students enter the classroom with long-held misconceptions that stem from their everyday experience, making them difficult to change [1, 2, 7]. Using the example of falling objects cited previously, students “know” from their experience that heavy objects such as metal weights fall more quickly than light objects such as papers or feathers. Subsequent teaching in physics might even inadvertently reinforce this misconception by teaching that gravity exerts a greater force on heavier objects and that force causes acceleration. For both these reasons and others, students can leave a course with their original misconception intact, even when they solve test problems correctly.

Fortunately, a substantial body of evidence exists to show that this situation can be improved. Hake [5], for example, demonstrated that instruction that emphasized conceptual understanding and interactive engagement methods significantly improved students’ conceptual understanding of physics compared to traditional instruction. Laws et al. [6] demonstrated even more dramatic results using active-engagement methods coupled with inquiry-based laboratory modules. The meaning of “inquiry-based” has many slightly different definitions [8], all of which share the key characteristic that students pose and answer questions through physical experience and direct observation rather than by listening to lecture or following a highly prescribed laboratory procedure. In this work, we define inquiry-based learning to be that which incorporates the defining features shown in Table 1 [6].

Table 1: Elements of Inquiry-Based Activity Modules [6]

(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

Results demonstrating the improved effectiveness of educational materials incorporating elements from Table 1 are shown in Figure 1.

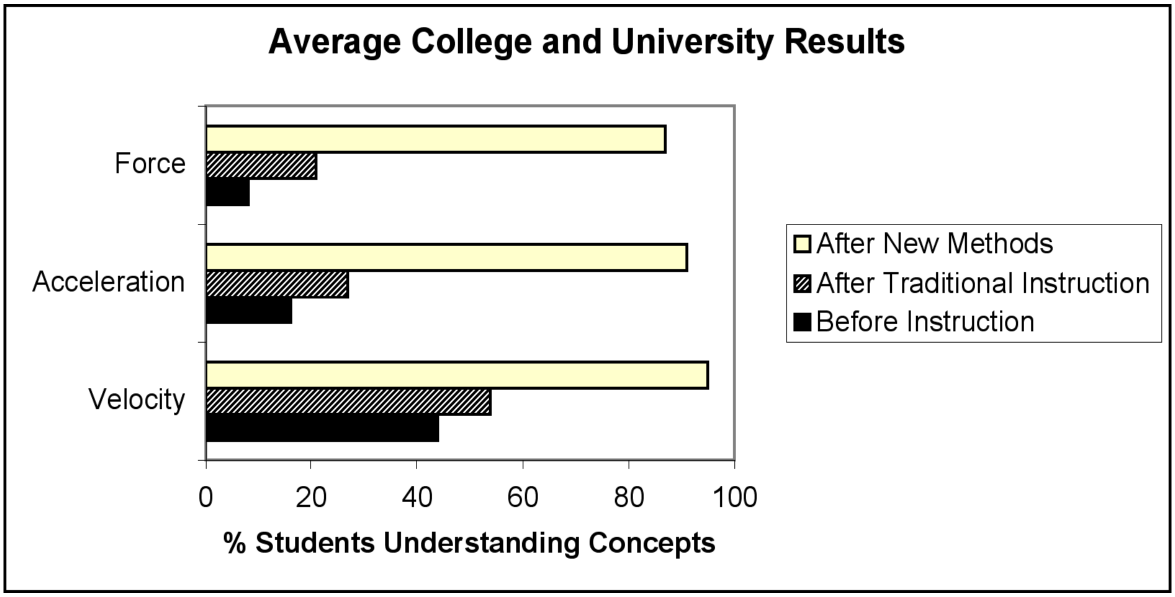

Figure 1. Active-engagement vs. traditional instruction for improving students' conceptual understanding of basic physics concepts (taken from Laws et al., 1999 [6]**)**

As can be seen in Figure 1, student understanding of fundamental concepts of force, acceleration and velocity were improved only marginally through traditional instruction. However, dramatic improvements were seen by incorporating the inquiry-based activity elements described in Table 1.

Reddish et al. [9] provided further support for these active engagement methods while demonstrating that the improvements were due to the type of instruction rather than time on task or the skills of the individual instructor. Moreover, this approach produces a win-win situation, because devoting time to active engagement methods produces students with both higher conceptual understanding *and* quantitative problem solving ability commiserate with or better than students in more traditional courses [10-12].

Uncovering student misconceptions requires valid and reliable assessment tools which can accurately assess conceptual understanding rather than factual knowledge or problem-solving ability. In the studies described above, improvements were documented through use of concept inventories rather than traditional exams. Concept inventories are multiple-choice tests specifically designed to assess student understanding of concepts. The well known Force-Concept Inventory has been in use for almost 20 years in physics [13]. A key feature in the design of these inventories is that the "wrong" answers, known as distracters, are specifically chosen to be attractive to students who possess common misunderstandings of the material. For example, "heavy objects fall faster than light objects because gravity exerts a stronger force on them" might be a good distracter for the example cited previously.

The success in physics education for enhancing students' conceptual understanding has depended on the availability of appropriate concept inventories and tested instructional materials designed to promote conceptual understanding. What has prevented engineering education from capitalizing on the success in physics for addressing students' misconceptions has been (1) in some cases, a lack of knowledge of the relevant literature (2) the lack of concept inventories to assess conceptual understanding in engineering and (3) the lack of inquiry-based educational materials for engineering applications similar to those shown to be effective in physics.

Each of these issues can be addressed. For example, there is a growing awareness of the benefits of active-engagement methods in engineering education as reflected by the literature [1, 14-16]. The benefits of active learning have been broadcast with increasing frequency and there are clear signs that the message is being heard [17].

With respect to assessment tools, there has been significant work recently to develop concept inventories for engineering. Concept inventories provide an excellent example of how assessment practices can lead to improvements in student education [18], because they are designed to uncover misconceptions students bring to the classroom. The importance of addressing these misconceptions is becoming increasingly clear [1]. For these reasons, there has been significant work in recent years to develop concept inventories in engineering [19-24]. These concept inventories provide promising tools to assess the effectiveness of the educational materials developed in this work or similar efforts.

The lack of appropriate educational materials to improve understanding of engineering concepts is the final missing piece required to capitalize on the successful model developed for physics education. Due in large part to successes such as described above, inquiry-based methods have been studied and adopted across the sciences [25-27] and mathematics [28, 29]. However, only very limited use of this approach has been seen in engineering education [30]. Addressing this gap is the specific goal of this project. The probability that successful educational materials can be developed for engineering is good since there is a proven model in physics from which to draw. The educational literature in physics provides well documented materials and explicit principles which can form the basis for similar educational materials in engineering. By building on materials developed in the sciences to develop materials specifically for engineering applications, we hope to bring the successes of the inquiry-based approach into broader use within our own field.

Procedure

Identifying General Engineering Concepts to Target

Developing educational materials must begin by identifying the fundamental misconceptions to be addressed. Fortunately, a Delphi study conducted through previous NSF funding has identified several concepts in thermal and transport science that are logical candidates by reason of being both important and difficult for students to master [24]. Specifically, this project targets the distinction between heat, energy and temperature as its target within Heat Transfer and entropy and the second law within Thermodynamics. Confusion of these concepts is widely recognized in the literature [7, 24, 31-33]. While the problem is widely recognized, there are no inquiry-based educational materials developed and proven effective for engineering students. Developing modules to address these key concepts within an engineering context and successfully demonstrating improved student understanding as a result of these modules is the goal of this project. This paper discusses our efforts to identify, develop, and test materials for improvement of conceptual learning in the area of heat transfer, which is a fall semester course and has been through one round of implementation and assessment. As Thermodynamics is a spring semester course, data from the implementation and assessment of the concept of entropy has not yet been collected.

While the Delphi study cited identifies general areas of misconceptions based on faculty perceptions, concept inventories were developed and given to engineering students to pinpoint more specific areas of confusion. Concept inventory results demonstrate that engineering students have significant misconceptions about heat vs. energy. In particular, student responses to a variety of concept inventory questions demonstrate that students often can not distinguish between those factors which affect the rate of heat transfer and those that affect the total amount of energy transferred in a given physical problem. The specific concept inventory questions designed to expose these misconceptions are shown in Table 2. These are a subset of a larger group of conceptual questions that were used to pinpoint areas where students had the most significant misconceptions.

Developing Inquiry-Based Activity Modules for Targeted Concepts

Educational materials to address the targeted concepts are being modeled after those developed by the Activity-Based Physics group [6, 34]. The general approach adopted by the physics activity group is in fact similar to that proposed by others [7, 33] and it is worth emphasizing that there is extensive empirical support for the approach's effectiveness [6, 12, 33]. In our prototype design, we target our materials to debunk those specific misconceptions which the pre-tests show to be most commonly held by students.

Inquiry-based activities were designed to incorporate each of the elements in Table 1. Students were put in teams and asked to predict what would happen in the first 3 specific situations identified in questions 1-6 in Table 2. Students were then given both physical experiments and/or computer simulations to test their predictions, after which they were asked to revise their thinking and explain how their thinking had changed if their predictions did not match reality. All the questions were conceptual in nature, using technology where appropriate. At the end of the specific activities, students were asked to step back and generalize what they had learned from the specific experiments with respect to heat transfer rates and energy balances.

Table 2: Relevant Conceptual understanding questions

Question	
1	Ice at $0^{O}C$ is melted by adding hot blocks of metal. One option is to use one metal block at a temperature of $200^{O}C$ to melt ice and a second option is to use two metal blocks each at a temperature of $100^{O}C$ to melt ice. The metal blocks are identical in every way except for their temperature, however, since there are *two* blocks at the lower temperature, they have twice the mass, surface area, etc. of the single block at $200\ ^{O}C$. Which option will melt more ice?
2	Which option will melt ice at a faster rate?
3	Either 15 ml of boiling water or 60 ml of ice cold water ($0^{O}C$) poured into an insulated cup of liquid nitrogen will cause some of the liquid nitrogen to evaporate. Which situation will ultimately cause *more* liquid nitrogen to evaporate?
4	Which situation will cause the liquid nitrogen to evaporate more *quickly*?
5	You would like to cool a beverage in an insulated cup either by adding large ice cubes or the same mass of finely chipped ice. Which option will cool the beverage to a colder temperature?
6	Which option will cool the beverage more quickly?
7	An engineering student has two beakers containing mixtures of dye in water. The first beaker has a 1% dye solution (1 gram of dye in 100 grams of water) and the second beaker has a 2% dye solution (2 grams of dye in 100 grams of water). The student would like to remove some of the dye from each beaker using a set of identical sponges. She places 2 sponges in the 1% dye solution and 1 sponge in the 2% dye solution. Which of these combinations will remove more dye from a beaker?
8	Which of these combinations will remove dye from the beaker faster?
9	Two identical beakers contain equal masses of liquid at a temperature of $20\ ^{O}C$. One beaker is filled with water and the other beaker is filled with ethanol (ethyl alcohol). The temperature of each liquid is increased from $20\ ^{O}C$ to $40\ ^{O}C$ using identical hot plates. It takes 2 minutes for the ethanol temperature to reach $40\ ^{O}C$ and 3 minutes for the water to reach $40\ ^{O}C$. Once a liquid had reached $40\ ^{O}C$, its hot plate is turned off. To which liquid was more energy transferred during the heating process?

Methods

In 2004, a broad series of concept inventory questions relating to temperature, energy and heat were given to 32 students in CHEG 300, the heat and mass transport course taken by 3rd year chemical engineers at Bucknell University, as well as to approximately 70 students at the Colorado School of Mines. Based upon their responses, it was determined that the most common misconception was that students believed that factors that affected the rate of heat transfer similarly affected the total amount of energy transferred. Consequently, three physical experiments were developed to specifically highlight the different factors which influence rate of energy transfer vs. total amount of energy transferred. These experiments were tested on small numbers of student and faculty volunteers and refined according to their input. Due to difficulty establishing clear, convincing and replicable results, one of the experiments was replaced with a computer simulation.

In the fall semester of 2005, revised inquiry based activities were formally piloted with a class of 21 students in CHEG 300. Students were given selected questions from the general concept inventory, including questions 1, 7, 8 and 9 in Table 2, in the first week of class. Their responses indicate their baseline conceptual understanding and showed significant misconceptions in the targeted area. Two weeks later, students were given a pre-lab handout asking them to make predictions about questions 1-6 in Table 2, all of which relate to the targeted misconception. These questions were asked again before the activity to get an accurate representation of student misconceptions just prior to the activity, since initial misconceptions may have shifted due to two weeks of instruction. In fact, there was some improvement on student responses to question 1.

Students then performed the inquiry-based activities which are the focus of this study. As discussed, the activities were designed to incorporate each of the elements in Table 1. The student response to questions 1-6 in Table 1 are their predictions for what should happen in specific situations. In order to confront existing misconceptions, students then conducted experiments that directly tested their responses. The experimental activities map directly to the questions. Specifically:

- Questions 1 and 2 relate to the situation of melting ice with different metal blocks. Therefore, a simulation of this system was programmed in Matlab using a graphical user interface to input simulated physical parameters and display model system behavior. Students “tested” their hypotheses by simulating the addition of 1 block at 200C and 2 blocks at 100C to ice at 0C, and were able to observe model results for the rate and amount of melting. These results could then be directly compared to their predictions on questions 1 and 2. Note that this system was found to be easier to simulate on a computer than to set up and observe experimentally, and therefore the simulation rather than a physical system was used to confront student preconceptions.

- Questions 3 and 4 relate to the boil-off rate and total amount of evaporation of liquid nitrogen to which either 60 g of ice water or 15g of boiling water were added. To test system performance, this situation was examined directly in the laboratory.

Approximately 100 gms of liquid nitrogen were placed in each of 2 styrofoam containers sitting on electronic balances. The specified amounts of boiling water and ice water were added to the respective cups and students observed the rates and amount of evaporation. Both could be observed by monitoring the display from the electronic balances, which were displayed on a computer, but the rate of evaporation was most easily observed by noting the amount of vapor cloud coming off and condensing from each cup. Students were told to look for this in advance in order to capture the relevant observation. Again, their observations could be compared directly to their predictions given in their pre-activities answers to questions 3 and 4.

- Questions 5 and 6 relate to the situation of cooling a beverage with the same mass of ice, added either as a single block or finely chipped pieces. Again, the laboratory activity mapped to this situation directly, allowing students to let physical reality determine what happens. Students added chipped ice and the same mass in a single "snowball" to two beakers of room temperature water in which temperature sensors were placed. The temperature-time behavior of the system was collected and displayed on a computer. The initial rates of cooling could be observed from the initial slope of the temperature vs. time line and the final temperature of the system at steady state could be easily observed.

A key component of inquiry-based instruction requires students to let real results, rather than the professor, correct misconceptions. Results from each of these activities allow just that in the case of questions 1-6. To encourage reflection and collaborative discussion, students were asked to submit their revised solutions to questions 1-6 one week after completing the activities described above. Students were allowed and encouraged to discuss their thinking with others in the class (although not the professor). Students were also asked explicitly to discuss how their thinking had changed and why for any questions to which their submitted answers did not match their original predictions made before the activities. Those revised answers are the "post activity" responses shown in Table 3.

These results show student responses to specific questions immediately after completing the inquiry-based activities. However, there were two concerns about getting at students' thinking that these responses do not address. First is the question of whether students would retain what they had learned through the activities. To assess that, students were asked questions 1-6 again at the end of the semester, approximately 12 weeks after the activities. Another concern was that students would be able to answer the questions correctly but because they remembered what happened in the activities rather than because they understood and could apply the fundamental concepts. To test this issue, students were asked questions 7, 8 and 9 at the end of the heat transfer course and the responses were compared to the responses students gave prior to the activities. These questions get at the same concepts (transfer rates vs. balances) but do so using different physical systems. Therefore, if students showed better performance on these questions after the activities, it would add strength to the argument that enhanced performance on questions 1-6 was due to gains in conceptual understanding rather than rote recall.

The concept inventory results were assessed to determine whether a) the change in the fraction of correct answers between the pre- and post- activity inventories were significant and b) the performance of the experimental group (2005) on the concept inventory was different from that of the control group (2004). The change in the fraction of correct answers for each question was assessed statistically, against the hypothesis that the differences between the two were generated by random chance. As responses to questions were either "right" or "wrong", the normal approximation to the binomial distribution (z statistic) was used to assess our results, and changes were deemed significant if there was $\alpha \leq 0.01$; that is, less than 99% chance of the change having occurred due to random chance. The number of samples (responses) for the control group (class of 2004) was 32, while there were 21 students in the class of 2005.

Results and Discussion

Students' conceptual understanding was monitored at different points in the semester. In the first week of classes, students were asked to complete a broad concept inventory. After two weeks of instruction, students were then given a conceptual quiz which included questions 1-6 in Table 2.

Table 3 shows the fraction of students giving correct responses to the questions in Table 2 in a variety of situations. The concept inventory shows that significant student misconceptions existed with regard to many (but not all) of the questions in Table 2 before the inquiry-based activities. Data from 2004 serves as a comparison, where no inquiry-based activities designed to dispel these misconceptions were presented. Note that a significant number of misconceptions exist (questions 1 and 9 in Table 2) both before *and after* traditional instruction. This is consistent with similar literature in physics education [2, 5]. While the control group did do significantly better on problem 1 after instruction, there was no statistically significant change in their answers for question 9. In the experimental year (2005) two weeks of instruction did produce a modest (and statistically significant) gain in conceptual understanding as measured in question 1 (see pre-activity: week 3 compared to week 1). This is consistent with the pre/post course data from the previous year of instruction in which inquiry-based methods were not used.

The short term effectiveness of the activities for addressing student misconceptions was measured by having students re-answer the questions immediately (within one week) of the activities (Table 3: Post-activity (week 4)). Note that the gain in student understanding as measured by the questions was complete, with all students answering all questions correctly. It is important to note that the instructors at no time provided correct responses to these questions or answered student questions relating to them.

Table 3. Fraction Students answering conceptual questions correctly. Bold text in columns 6 and 7 indicate a statistically significant improvement from Week 3 at a minimum of 99% confidence. n(2004) = 32; n(2005) = 21.

Question	Traditional Week 1 (2004)	Traditional Week 14 (2004)	Inquiry Week 1 (2005)	Pre-Activity Week 3 (2005)	Post-activity Week 4 (2005)	Post-Course Week 15 (2005)
1	15%	38%	42%	62%	**100%**	**90%**
2				67%	**100%**	**81%**
3				62%	**100%**	**95%**
4				76%	**100%**	**90%**
5				81%	**100%**	**100%**
6				95%	100%	100%
7			10%			**86%**
8			29%			**67%**
9	50%	47%	38%			**62%**

The long term impact of the activities on students' conceptual understanding was determined by asking the questions again 12 weeks after the laboratory activities. The results are also shown in Table 3. Note that while student retention was less than perfect, it was quite high with students averaging a 93% correct response on the 6 questions. The gains shown by students using the activities are statistically significant at a minimum of 99% confidence for all questions but number six. Student gains in the experimental group were also significantly better than those in the 2004 control group. The final gains on questions 1 and 9 are greater for the experimental group than for the control group at the 99.9% confidence level.

While students were never provided correct answers by the instructor, it is possible that students might answer correctly based on their memory of what happened in the activities rather than because of conceptual learning gains. To test this hypothesis, students were given an analogous problem to question 1 using mass transfer concepts (question 7 and 8 in Table 2). The improved number of correct responses of questions 7 and 8 indicates that students' conceptual understanding did improve and could be applied to similar but distinct situations. In addition, the improvement of students' conceptual understanding of rates vs. energy balances can be seen in the improvement of students' correct responses on question 9. While the improvement was not as great as that found for questions 1-6, it was a clear improvement on results found during the previous year when inquiry-based activities were not used.

Conclusion

Significant research demonstrates that "teaching by telling" does little to address fundamental misconceptions that students bring to the classroom. Rather, conceptual learning is best promoted by inquiry-based activities in which reality, rather than the professor, can dispute student misconceptions. This project seeks to draw on the relevant research base and successful model in physics to develop similar educational materials for engineering courses. The project develops prototype inquiry-based educational materials which address common, documented student misconceptions in the areas of heat transfer and thermodynamics. The effectiveness of these materials was assessed through the use of concept inventories and they were found to be effective for both short term and long term improvements of students' conceptual understanding.

The modules will be refined through two years of testing by Bucknell students. The results presented here document the first half-year of testing. The three inquiry-based activities developed for heat transfer were successful in improving student conceptual understanding of the different factors impacting *amount* and *rate* of heat transfer. Activities included one where students melted equal masses of chipped ice and "snowball" ice in identical water baths, one where liquid nitrogen was boiled using a large mass of cold water or a smaller mass of hot water, and finally a simulation where students could observe the effect of mass, density, and surface area on the heat transfer from one or more blocks. Ongoing work hopes to show similar improvement in the understanding of entropy after use of inquiry-based activities. Both the heat transfer and the thermodynamics activities will be further refined based on student comments and input from outside test sites, and will be tested with students again next year. Successful implementation of this pilot-program will allow us to generate self-contained modules for use at other universities, as well as lay the groundwork for further development of modules addressing additional student misconceptions.

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