REPAIRING STUDENT MISCONCEPTIONS IN HEAT TRANSFER USING INQUIRY-BASED ACTIVITIES

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Anyone who's taught for more than a week knows that students don't learn everything that we teach. While we accept that students will either fail to absorb or subsequently forget many details, we hope that our students learn the "big ideas" or concepts from each course. Unfortunately, extensive research suggests that many science[1-6] and engineering[7-11] classes do little to foster deep conceptual understanding. Traditional instruction is particularly ineffective for promoting significant conceptual change.

This is an important failing because mastering fundamental concepts is critical for developing technical expertise. One of the key differences between experts and novices is not just that experts know more information; it's that the information is organized efficiently around core concepts.[12] This organized storage of information is what allows for its easy retrieval and use by experts.

The inefficiency of traditional instruction for promoting conceptual learning often stems from instructors' naïve view of the learning process. We assume that as long as instructors know what they're talking about, and as long as they explain it clearly—and as long as the students come to class and pay attention—students will absorb the conceptual understanding that the expert has. Unfortunately, it just doesn't work that way. This "teach by telling" model is particularly ineffective when students bring misconceptions to the classroom. In those cases, learning involves not just getting students to absorb new information, it requires students to change something that they currently believe. Often these beliefs are based on a lifetime of real-world experience and are reinforced by what students learn in school. For example, many adults believe that the seasons are caused by how close the Earth is to the sun. They often believe this for two reasons. First, they have a lifetime's experience telling them that they feel warm when

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they are closer to something hot (like a campfire). Second, they learn in school that planets travel in elliptical orbits and many have the mistaken belief that the Earth spends part of the year much closer to the sun than at other times.

In these situations where students' life experience and academic learning both contribute to a seemingly well-supported misconception, it can be quite difficult for students to change their minds. This is because change is as much an emotional process as an intellectual one. Change means letting go of one idea that seems to make sense and grasping after something new before that new idea is really comfortable for the learner. Most engineering instructors underestimate the emotional price of change and so often mistakenly believe that students will quickly drop their existing preconceptions when an instructor explains a concept correctly.

Most effective strategies for promoting conceptual change rely less on "teaching by telling" and are instead "inquiry-based." Bernhard provides a good overview 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.[13] Prince and Felder[14,15] provide extensive evidence that inquiry-based instructional methods are effective for promoting a variety of educational outcomes.

The goal of many inquiry-based methods is to produce a teachable moment for students, often by promoting cognitive conflict. To do this, instructors put students in situations where they unavoidably confront their misconception. With students who believe that the seasons are caused by the Earth's proximity to the sun, for example, the instructor might produce cognitive conflict by asking students to explain why it's winter in Argentina when it's summer in Canada. That conflict—recognizing that proximity to the sun cannot simultaneously produce different seasons in the Northern and Southern hemispheres—does not in itself explain the cause of the seasons. It does, however, create the situation where students are more ready to learn what the instructor has to say because they can see for themselves that their current thinking is inadequate.

Promoting cognitive conflict as an approach for fostering conceptual change has found several applications in science and engineering education over the past couple of decades. The authors have adopted a variation of this approach for the instruction of both heat transfer and thermodynamics for engineering students. The model draws most heavily from that developed by Priscilla Laws and colleagues as part of the Workshop Physics group.[16] The elements of that model are shown in Table 1. This approach is similar to that proposed by others[17,18] and has extensive empirical support.[16,19]

In this paper, we illustrate how we've adopted this model for teaching four particular heat transfer concepts that are known from the literature to be both important to know and difficult for students to master. These heat transfer concepts tend to be ones where students have a number of persistent misconceptions. Those targeted concept areas for this study and some common student misconceptions are shown in Table 2.

TABLE 1
Elements of inquiry-based activity modules

(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

TABLE 2
Targeted conceptual areas and common student misconceptions

Content Area	Misconception
1. Rate vs. Amount	Many students seem to believe that factors that increase the rate of heat transfer always increase the amount of heat transferred as well. These misconceptions carry over to related fields such as mass transfer.
2. Temperature vs. Perception of Hot and Cold	Many students think that temperature is a measure of how hot or cold things feel. Many students do not understand that other factors, such as the rate of heat transfer, frequently affect how hot or cold something feels.
3. Temperature vs. Energy	Students commonly believe that temperature is a direct measure of the energy in an object, so something at a higher temperature always has more energy.
4. Radiation	Students are often confused about the effect of surface properties such as color on the rate of radiative heat transfer, for example believing that black surfaces hold on to energy and therefore emit radiation more slowly than white surfaces.

The justification for the selection of these targeted concepts areas is given in detail in Prince, *et al*.[20] and summarized briefly here.

- ***Rate vs. Amount:*** *This misconception area was identified in the development of both the Thermal and Transport Concept Inventory (TTCI)*[8,21] *and the Heat Exchange Concept Inventory (HECI).*[9,22-24] *Specifically, both sets of studies showed that engineering students frequently confound factors that affect energy transfer rates with those that affect total amounts of energy transfer.*
- ***Temperature vs. Perceptions of Hot and Cold:*** *The literature suggests that both adults and children often*

TABLE 3 Design elements of inquiry-based activity modules	
I.	Materials should be available in a standard chemical engineering laboratory OR
II.	Materials should be available at a store such as Walmart for less than $25
III.	Experiments should take about 15 minutes
IV.	Students should capture in writing both their prediction and reflection.

TABLE 4 Materials for crushed vs. block ice
2 1-liter beakers filled with room-temperature water
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 (may be replaced by timed measurements with a pair of analog thermometers)
2 temperature sensors specific to the data logging software being used

rely upon intuitive understandings of temperature as a measure of how hot or cold something feels.[11,25] Work with engineering students during the development of the TTCI[8] and our own studies of engineering students at a number of colleges and universities[9,22,24] showed that this misconception is prevalent among undergraduate engineering students.

- ***Temperature vs. Energy:*** *Streveler, Litzinger, Miller, and Steif[11] cite temperature vs. energy as a topic where students commonly have misconceptions, most notably that temperature is a direct indicator of the quantity of energy contained in an object. This finding was drawn in part from their Delphi study[26] that asked engineering educators to identify topics that were both important and difficult for their students to understand. Further support for the prevalence of this misconception among engineering students is provided by References 8 and 11. Our own research findings are consistent with these earlier studies.[9,22]*
- ***Radiation****: References 20 and 26-28 have identified thermal radiation as a topic where engineering students frequently have misconceptions.*

In the remainder of this article, we provide details for the inquiry-based activities that we've developed and tested to promote understanding of these concept areas and to repair common student misconceptions. After describing each activity, we briefly discuss the methodology used to analyze the effectiveness of the activities for promoting conceptual change among undergraduate engineering students and then discuss the results.

INQUIRY-BASED ACTIVITIES

Two inquiry-based activities were created for each of the four concepts given in Table 2. Our inquiry-based activities follow a standard format. Each begins with students reading a description of an experimental situation, then predicting the outcome they will observe and giving their reasoning for this prediction in writing. Then students perform an experiment or, in cases where this is impractical, run a simulation. The experiment/simulation is designed to produce cognitive conflict by failing to conform to common student predictions. Finally, students are asked to reconsider their prediction and reflect upon what they have learned.

The following descriptions focus on the experiment or simulation segment of the activity and provide enough detail for readers to replicate these in their own courses. For copies of the worksheets containing the prediction and reflection questions, please contact the first author.

The activities drew inspiration from concept inventory questions used in the HECI.[20] Whenever possible, the activities are physical re-creations of particular questions. When this was not possible, the activities closely mimic the question in a more experimentally accessible manner; for example, the HECI questions most similar to the "heat lamp" activity ask about temperature change in metal cans placed in sunlight, while the experiment uses metal tubes under a heat lamp. Not every question from the HECI is echoed in an activity. Of the 36 questions in the HECI, nine are considered to be directly represented in an activity.

The design guidelines given in Table 3 were adopted in order to promote usability in a wide variety of settings. Items I, II, and III were heuristics developed to make it practical to use these activities with minimal redesign of existing courses. Item IV reflects that the observation of a discrepant event is not usually sufficient to repair a misconception; the learner must actively engage in reconstructing his or her understanding around the new knowledge. The written component encourages learners to spend sufficient time doing so.

RATE VS. AMOUNT

Crushed vs. Block Ice activity

Students begin by predicting which will cool a glass of water faster—crushed ice or an equal mass of ice as a single block? And of these two, which will cool the water more? While many students correctly predict that the crushed ice is faster, they also incorrectly predict that the crushed ice will bring the water to a lower temperature, conflating faster energy transfer with more heat transfer. Required materials for the activity are shown in Table 4.

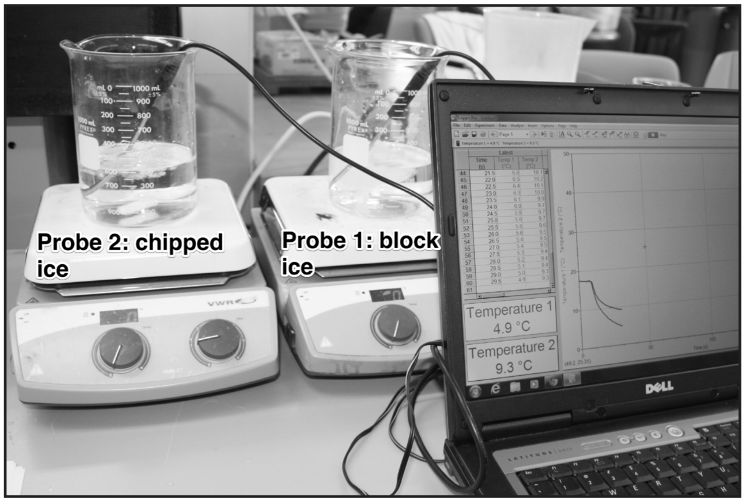

Figure 1. Crushed Ice vs. Block Ice activity. The more rapid cooling of the chipped ice can be seen on the screen. When fully melted, both systems are at the same temperature.

TABLE 5 Materials for Melting Ice Simulation
Device with internet access (computer, tablet, phone)
Browser capable of running javascript (Firefox, Chrome, Safari, IE)
Access: <http://www.facstaff.bucknell.edu/mvigeant/HT_JS/Melting_Ice/melting-ice.html>

For the experiment, shown in Figure 1, students start with identical beakers of water and two identical containers of crushed ice. They then compress the contents of one of the containers of crushed ice into a "snowball" with their hands. Students simultaneously add the crushed ice to one beaker and the "snowball" to the other and log the resulting temperature change over time. While the chipped ice system cools more rapidly, both cups ultimately reach the same temperature.

Melting Ice Simulation activity

Students start this activity (materials required shown in Table 5) with several questions that ask them to predict how effective various configurations of high-temperature metal blocks will be at melting ice. For example, will two identical metal blocks at 100 ºC be as fast as one metal block, identical to the first two, but at 200 ºC? As with the prior inquiry-based activity, students tend to confuse speed and amount. In the case of the blocks cited above, both situations result in identical ice melting rates as well as identical amounts of melted ice.

This activity was created as a simulation (shown in Figure 2) due to the difficulty of running the physical experiment—for example, the blocks must be identical and the temperatures precise and the contact area between each block and the water or melting ice must be consistent. Without meeting each of

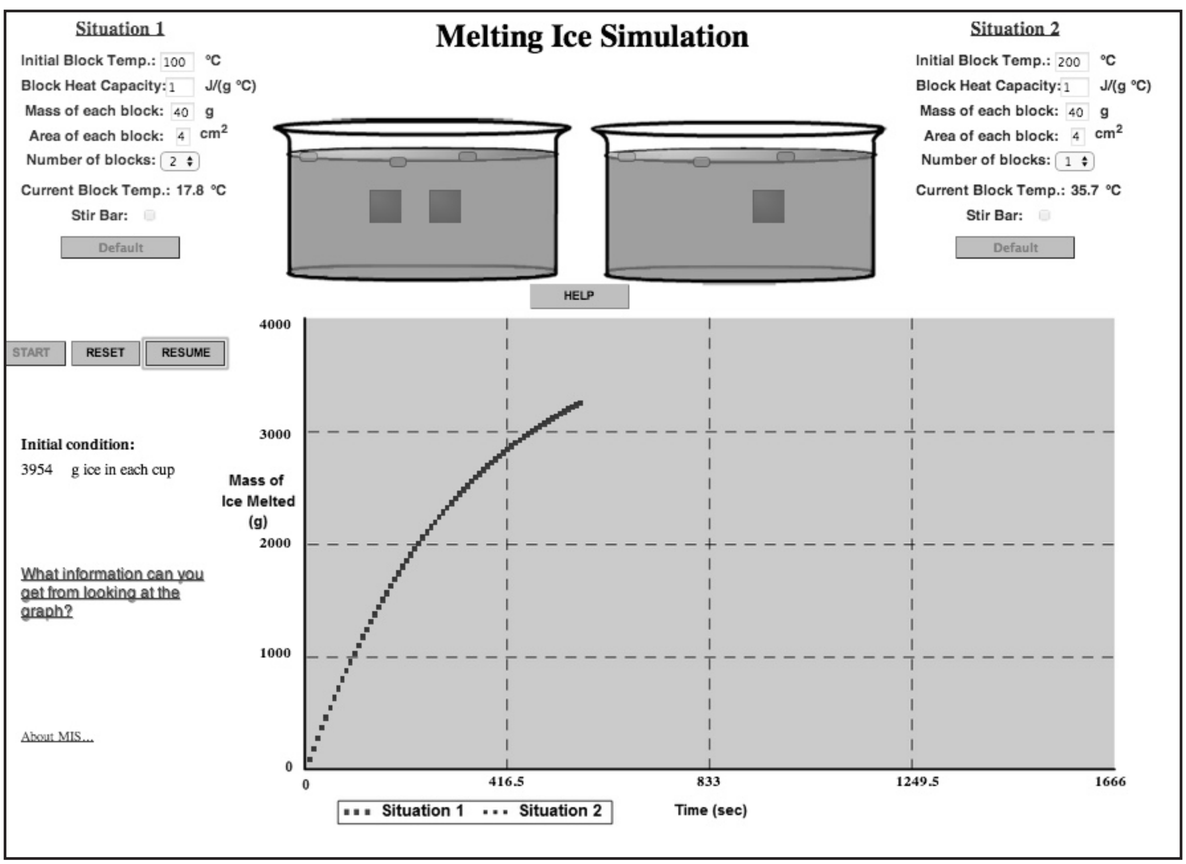

Figure 2 (left). Screen shot of Melting Ice Simulation, showing identical ice-melting behavior of two metal blocks at 100℃ and one metal block at 200℃.

Figure 3. *Two items from the Human Thermometer activity: The stainless-steel knife feels significantly "colder" than does the plastic cutting board, although both are at room temperature.*

these requirements, the accumulated slight differences risk confirming students' misconceptions rather than dispelling them. Another benefit of the simulation is that it affords easy manipulation of heat capacity, mass, and temperature that would be time consuming or impossible to do within a conventional laboratory period.

TEMP. VS. PERCEPTION OF HOT AND COLD

Water Bath activity

Students are first asked to predict whether temperature is a good measure of how hot or cold something will feel, explaining their answers. They then test their predictions in the activity, materials for which are shown in Table 6. Students tend to predict that their sense of something being "hot" aligns accurately with its temperature.

Students put one hand in a container of ice water and the other in the container of warm water. They then transfer both of their hands to the room-temperature beakers. The hand that has just experienced ice water feels the room-temperature water as hot, while the hand from warm water feels the room-temperature water as cold. This experiment positions students well mentally for the following activity. While the Water Bath activity proves that sensation is not a measure of temperature, it should leave them wondering what it is they are feeling? This is addressed by the Human Thermometer.

Human Thermometer activity

Here, students again predict the relationship of how objects feel to their temperature and also how objects feel to their ability to melt an ice cube rapidly. Required materials are shown in Table 7.

Students tend to predict that their sense of something being "hot" aligns accurately with its temperature.

After their predictions, students briefly touch each item (see Figure 3) and rank it on a 5-point scale from "very cool" feeling to "very warm." They are asked to consider the data in Table 8 and identify which properties best account for their perceptions.

They also observe that an ice cube placed on a metal sheet melts much more rapidly than does an ice cube placed on a plastic sheet. This activity is based upon the Human Thermometer model-eliciting activity by Miller.[29,30]

TABLE 6
Materials for Water Bath

A 1-l beaker of ice-water
A 1-l beaker of warm water, about 45 ºC
2 1-l beakers of room-temperature water
A thermometer or thermocouple
(hot plate, if warm tap water is not available)

TABLE 7
Materials for Human Thermometer

A steel table knife
A piece of soft wood such as a pine or balsa block
A polystyrene or Styrofoam cup
A glass cup
A piece of carpet
A piece of flat plastic
A piece of flat aluminum (these may come from a hardware supply or may be a cutting board and a cookie sheet)
(a thermometer is optional)

TABLE 8
Material properties for Human Thermometer activity[31]

Material	ϱ (kg/m^3)	cp (J/kg ^{o}C)	k (W/m ^{o}C)	α x 10^7 (m^2/sec)
aluminum	2700	903	237	972
plastic	~1000	~1700	~0.2	~1.2
steel table knife	7913	456	16	44.3
soft wood	513	1380	0.115	1.62
Styrofoam cup	104	1817	0.13	6.88
glass cup	2530	840	1.0	4.70
carpet	300	1400	0.06	1.43
human skin	1000	4180	0.29	0.69

TEMPERATURE VS. ENERGY

Liquid Nitrogen activity

Can you evaporate more liquid nitrogen by adding 100mL of boiling water to it or by adding 500mL of ice water to it? In responding to this question, many students focus on the impact of the temperature rather than on the quantity of water and its energy content. The activity is shown in Figure 4 and required materials are shown in Table 9.

While the intensive energy is higher for boiling water, this is more than accounted for by the addition of five times as much ice water.

Students measure out identical masses of liquid nitrogen into the two cups, and then simultaneously add 500g of ice water to one and 100g of boiling water to the other. They then record the mass shown on each balance after about one minute when the mass has stabilized. The condensed water vapor "cloud" emerging from each cup is a good proxy for the rate of evaporation, which students may note is indeed greater initially for the boiling water.

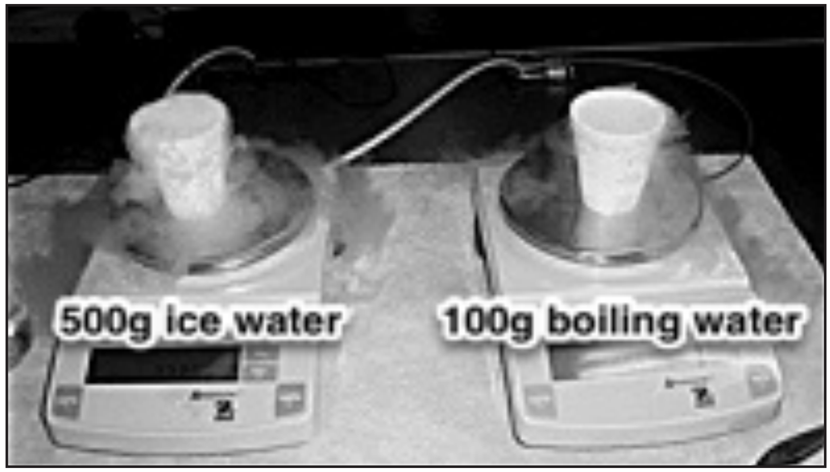

Figure 4. *Liquid Nitrogen activity; in the cup on the left liquid nitrogen will ultimately evaporate more than will that in the system on the right, even though the water added to the left-hand cup is at a lower initial temperature. The difference in rate is evident from the "cloud" surrounding the cup.*

TABLE 9 **Materials for Liquid Nitrogen**
~2 L of liquid nitrogen (enough for repeated runs)
2 ~100mL Styrofoam containers (coffee cups)
2 digital balances with reasonable accuracy in the 0-200 gram range
~500g of ice water
~100g of boiling water
A hot plate to produce boiling water
Insulating gloves for handling liquid nitrogen and boiling water containers

TABLE 10 **Materials for Adiabatic Valve simulation, created by John M. Persichetti**
Device with Microsoft Excel
Access: <http://bit.ly/1yQQii1>

TABLE 11 **Materials for Steam Pipes**
Plumbing to the building / laboratory steam source
3 copper pipes, attached to steam source with valves and ending in a trap, ~1m long with the following surface finishes: polished copper painted white painted black
Beakers to capture water emptied from the trap

* Also available as a simulation: <http://www.facstaff.bucknell.edu/mvigeant/HT_JS/Radiation_Pipe/radiation.html>

Adiabatic Valve activity

Many of our students have experienced the sensation of holding a can that is cooling rapidly as its valve is opened, for example with whipped cream. Combined with their ongoing education in physical chemistry and some misapplications of the ideal gas law, this leads students to predict that the temperature of all gasses expanding through an adiabatic valve will drop. Students test this prediction by accessing the simulation link given in Table 10.

The simulation allows students to change the inlet and outlet pressure flowing through the valve as well as to explore the behavior of different gasses (helium, nitrogen, argon, methane, and carbon dioxide). These gasses were chosen because of their varying Joule-Thomson coefficients so that as the gasses pass through the valve, sometimes the temperature increases and sometimes it decreases. For situations where the gas remains essentially ideal before and after the valve, the temperature change is very small. Since the energy of the system is unchanged while temperature change varies, this experience emphasizes how temperature is not a direct indicator of the energy of a system.

RADIATION

Polished and painted Steam Pipes activity

Both radiation activities make students reconsider their assumptions about the effect of color on radiative heat transfer. Students tend to assume that color is the controlling factor in both adsorption and emission of radiative energy. In this activity, materials for which are shown in Table 11, students predict the rate of heat transfer from three copper pipes—one painted white, one painted black, and one polished copper—each containing saturated steam.

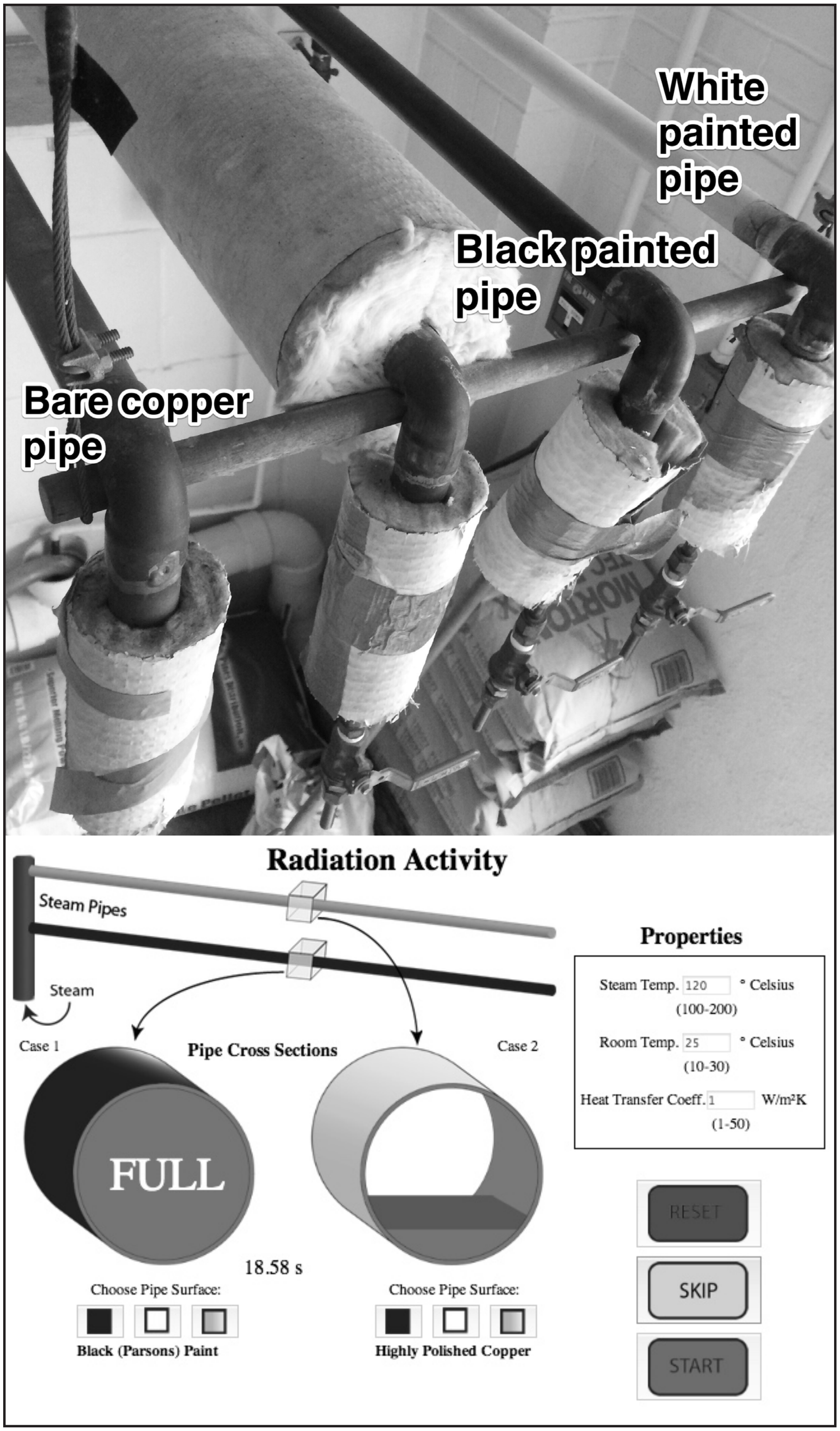

Figure 5. *Steam Pipe activity. Top: physical experiment; bottom: simulation. The rate of condensation of steam inside the pipe is a function of the radiative heat loss from the pipe. Bottom: simulation replicates the physical experiment pair-wise, so students must run at least two simulations to compare all three surface treatments. The simulation also affords control over room temperature.*

Students test their predictions using the experimental apparatus shown in Figure 5. The rate at which steam condenses is directly proportional to the net heat loss from each pipe. Students are surprised to discover that not only does paint color matter very little, both painted surfaces transfer heat more rapidly than the shiny copper.

Heat Lamp activity

This activity also invites students to consider the impact of color on radiative heat transfer. In this case, however, students observe how surface properties impact both adsorption and emission. The experiment is shown in Figure 6 and required materials are listed in Table 12.

After recording their predictions, students test the behavior by running the activity. Room-temperature tubes, black, white, and polished copper, are arrayed beneath the heat lamp, and students observe the rate at which their temperatures rise. Students generally expect the black tube to heat most rapidly, which it does. Students also predict and observe what happens as the tubes cool. To bring the tubes to a uniform elevated temperature, students immerse them in boiling water immediately prior to the start of the cooling measurements. Here, students are surprised to discover that paint color is of relatively little consequence. Students are provided with a table of emissivities which they then use to explain why color was not a good predictor of behavior.

METHODOLOGY

This study examined the effect of eight inquiry-based activities on improving undergraduate engineering students' conceptual understanding in the four targeted concept areas shown in Table 2. A quasi-experimental design with intact groups was used to assess learning gains and to determine whether there was a significant difference in conceptual understanding of targeted concepts between a test group that was given the inquiry-based activities and a control group that was not.

Students' conceptual understanding was assessed using the HECI. The HECI is one of several concept inventories (validated multiple-choice instruments designed to assess conceptual understanding rather than factual information or problem-solving skills) developed for engineering topics. It has 36 questions covering the four targeted concept areas shown in Table 2. A further discussion of the development, structure, and validation of the HECI is provided in Prince, Vigeant, and Knottis.[20] The instrument has demonstrated acceptable levels of internal consistency reliability and content validity in previous research.[32] Estimates of internal consistency reliability determined from post-test scores with the current sample were high. Using the Kuder-Richardson Formula #20 (KR#20) internal reliability was 0.87. Using Split-Half, the reliability was 0.85. According to Fraenkel, Wallen, and Hyun,[33] a reliability of at least 0.70 is considered acceptable for research purposes.

Participants completed either a paper or computerized version of the HECI within the first two weeks of the course (pre-test) and within the last two weeks of the course (post-test). Students were told to complete the concept inventory individually within one hour without the assistance of any reference materials. Measurements for the control group assessed pre/post changes on the HECI under normal classroom conditions, that is, without the use of the activities. The experimental group completed activities at points spread throughout the semester, in an order and in settings that made best pedagogical sense to the instructor.

Descriptive statistics examined changes in knowledge, as measured by the mean scores of participants on the entire concept inventory as well as on each conceptual area sub-test. One-way Analysis of Variance (ANOVA) was used to initially examine the differences between pre- and post-test scores of the two groups (control and activities). If a significant difference between the groups was found on the pre-test, Analysis of Covariance (ANCOVA) was done on post-test differences using pre-test scores as a covariate. 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. The extent of the difference between the means of the two groups was explored using effect sizes. Cohen's *d* was calculated for t-tests and Partial Eta-Squared was used with ANOVAs.

Demographics

The HECI was administered to a total sample of 986 students in 25 course offerings at 15 different schools. 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 HECI was given as a pre-test of existing knowledge to a control group of 373 undergraduate engineering students at 10 different universities or colleges; 353 reported they were currently in a heat transfer course. Of the 373 respondents, 344 completed the concept inventory again after instruction.

The test (activities) group consisted of a sample of 576 students at eight different undergraduate institutions. The HECI was administered as a pre-test of existing knowledge to this group. Of the 576 respondents, 497 completed the concept inventory again after instruction that included administration of the inquiry-based activities; 488 reported they were currently in a heat transfer course. There were eight activities tested in this study, two targeting each of the four concept areas of the HECI.

Demographic information for both student samples is shown in Table 13 (following page).

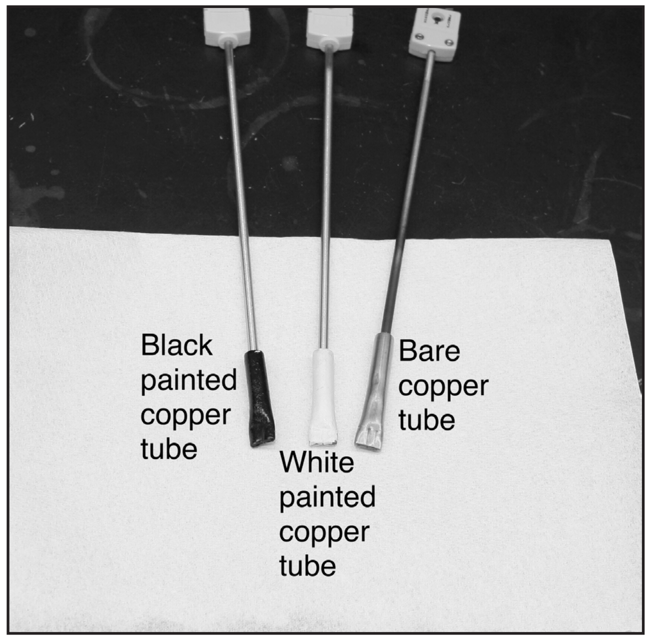

Figure 6. *Radiation Heat Lamp experiment, showing the copper tubes affixed to the thermocouple probes. Heat lamp is at the position of the viewer, incident on the three tubes.*

TABLE 12
Materials for Heat Lamp

A heat lamp suspended by a ring stand or other height-repositionable stand
3 ~5 cm lengths of copper tubing with a diameter chosen to fit snugly over thermocouples with the following surface finishes: polished copper painted white painted black
3 thermocouples, ideally attached to data-logging software on the computer (may record data by hand)
Beaker of boiling water, large enough to accommodate all three copper-clad thermocouple probes
Hotplate to boil water

RESULTS

A summary of the descriptive statistics as assessed by pre/post measurements using the HECI for both the control and test groups is shown in Table 14. Significant differences between the mean post-test scores of both groups are noted.

Participants in the test group had lower mean pre-test scores than the control group on the overall concept inventory as well as all of the sub-tests, and this was accounted for in the analysis. One-way analysis of variance (ANOVA) showed that the overall mean pre-test scores for the two groups were significantly different although the effect size was small; [$F(1,947) = 6.46$, $p < .05$, partial $\eta 2 = .01$]. One-way ANOVAs also revealed that the mean scores of the two groups were significantly different with small effect sizes on two pre-sub-tests: Temperature vs. Perceptions of Hot/Cold, [$F(1, 941) = 5.64$, $p < .05$ partial $\eta 2 = .01$] and Thermal Radiation, [$F(1, 930) = 10.74$, $p < .01$, partial $\eta 2 = .01$]. In all cases, the control group had a significantly higher mean pre-test score than the test group.

After instruction, an analysis of covariance (ANCOVA) was conducted on differences in the post-test scores on the entire HECI using pre-test scores as a covariate. A statistically significant difference with a large effect size was found between the two groups on the post-test when pre-test was controlled for; [$F(1, 801) = 178.05$, $p < .01$, partial $\eta 2 = .18$]. The test group scored significantly higher than the control group on the post-test.

Both teaching approaches improved students' scores on the post-test, although the experimental group improved significantly more. 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, respectively; $t(466) = -27.1$, $p < .01$, $d = 1.25$ and $t(336) = -7.74$, $p < .01$, $d = .42$. There was a very large effect size for the test (activities) group and a moderate effect size for the control (no activities) group. According to Fraenkel, Wallen, and Hyun,[33] any effect size of .50 or larger [for Cohen's *d*] "is an important finding" (p. 248).

The post-tests are given at the end of the semester, possibly 10 weeks or more since the first activities were completed, which makes the improvements particularly striking. An entire semester of baseline instruction results in a post-test score increase of no more than 10 percentage points, while the addition of two ~15-minute activities more than doubles the impact of the course in students' understanding in these areas.

TABLE 13
Demographics of student samples for both control and test groups

Control Group (no activities)	Test Group (w/ activities)
Totals: n = 373 (pre), 344 (post)	N = 576 (pre), 497(post)
Gender: 73.4% Male, 26.6% Female	Gender: 71.9% Male, 28.1% Female
Ethnicity: 80.9% White, 9.8% Asian/Pacific Islander, 2.9% African American, 2.4% Hispanic	Ethnicity: 69.0% White, 15.5% Asian/Pacific Islander, 2.3% African American, 4.5% Hispanic
Academic Major: 39.5% Chemical Engineering, 47.4% Mechanical Engineering, 13.1% Other	Academic Major: 56.1% Chemical Engineering, 31.4% Mechanical Engineering, 12.5% Other
Class Year: 30.5% Seniors, 61.2% Juniors, 7.9% Sophomores, 0% Freshman, 0.3% Graduate Students	Class Year: 16.7% Seniors, 64.5% Juniors, 17.3% Sophomores, .5% Freshman, 1.0% Graduate Students

TABLE 14
Mean pre/post performance data by content area, with and without activities; significant differences between post-tests noted

Content Area	Mean Score, Control (no activities)		Mean Score, Test (w/ activities)	
	Pre-Test n = 373	Post-Test n = 344	Pre-Test n=576	Post-Test n=497
Temperature vs. Energy	53.6%	56.4%	52.1%	62.7%**
Temperature vs. Perceptions of Hot or Cold	61.4%	70.4%	57.9%	73.7%*
Rate vs. Amount	36.8%	42.6%	33.5%	64.4%**
Thermal Radiation	44.6%	50.8%	40.5%	63.1%**
Overall	**49.2%**	**54.4%**	**46.5%**	**66.1%****

* Statistically significant difference between the mean post-test scores of the two groups at the $p < 0.05$ level.
** Statistically significant differences between the mean post-test scores of the two groups at the $p < .01$ level.

CONCLUSIONS

This study examined the development and testing of several inquiry-based activities for repairing student misconceptions in heat transfer. This paper describes the activities in sufficient detail for instructors to adopt them in their own courses. The concept areas and associated misconceptions targeted in this study have been identified in the literature as both important and difficult to repair through traditional instruction. The study demonstrated that these inquiry-based activities significantly increase student performance on measures of conceptual understanding, both in the aggregate and for each of the targeted concept areas of the HECI. Taken as a whole, this work contributes to our understanding by adding to what is at present a small database of the effectiveness of such activities with undergraduate engineering students.

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REFERENCES

1. Deslauriers, L., E. Schelew, and C. Wieman, "Improved Learning in a Large-Enrollment Physics Class," *Science*, **332**(13), 862 (2011)
2. Center for Development & Learning, Covington, LA, "Improving Teaching, Improving Learning: Linking Professional Development to Improved Student Achievement." <http://www.eric.ed.gov/ERICWebPortal/detail?accno=ED455226>
3. Lightman, A., and P. Sadler, "Teacher Predictions Versus Actual Student Gains," *The Physics Teacher*, **31**, 162 (1993)
4. Sahin, M., "Effects of Problem-Based Learning on University Students' Epistemological Beliefs About Physics and Physics Learning and Conceptual Understanding of Newtonian Mechanics," *J. Science Education and Technology,* **19**(3), 266 (2010)
5. Smith, J.P., A.A. diSessa, and J. Roschelle, "Misconceptions Reconceived: A Constructivist Analysis of Knowledge in Transition," *J. the Learning Sciences*, **3**(2), 115 (1993)
6. Suping, S. "Conceptual Change Among Students in Science," ERIC Digest ED482723 (2003)
7. Krause, S., J. Decker, and R. Griffin. "Using a Materials Concept Inventory to Assess Conceptual Gain in Introductory Materials Engineering Courses," Paper presented at the Frontiers in Education Conference, Boulder, CO (2003)
8. Miller, R.L., R.A. Streveler, B.M. Olds, M.T.H. Chi, M.A. Nelson, and M.R. Geist. "Misconceptions About Rate Processes: Preliminary Evidence for the Importance of Emergent Conceptual Schemas in Thermal and Transport Sciences," Proceedings ASEE Annual Conference, Chicago (2006)
9. Prince, M., M. Vigeant, and K. Nottis, "Assessing Misconceptions of Undergraduate Engineering Students in the Thermal Sciences," *Int. J. Engineering Education*, **26**(4), 880 (2010)
10. Steif, P., A. Dollar, and J.A. Dantzler. "Results From a Statistics Concept Inventory and Their Relationship to Other Measures of Performance in Statistics," Proceedings at the Frontiers in Education Conference, Indianapolis, IN (2005)
11. Streveler, R.T., T. Litzinger, R. Miller, and P. Steif, "Learning Conceptual Knowledge in the Engineering Sciences: Overview and Future Research Directions," *J. Eng. Ed.*, **97**(3), 279 (2008)
12. Bransford, J., A. Brown, and R. Cocking, *How People Learn: Brain, Mind, Experience and School*, Washington, D.C.: Commission on Behavioral and Social Science and Education, National Research Council (2000)
13. Bernhard, J. "Improving Engineering Physics Teaching—Learning From Physics Education Research," Paper presented at the Physics Teaching in Engineering Education, Budapest (2000)
14. Prince, M., and R. Felder, "The Many Faces of Inductive Teaching and Learning," *J. College Science Teaching*, **36**(5), 14 (2007)
15. Prince, M., and R. Felder "Inductive Teaching and Learning Methods: Definitions, Comparisons, and Research Bases," *J. Eng. Ed.*, **95**(2), 123 (2007)
16. Laws, P., D. Sokoloff, and R. Thornton, "Promoting Active Learning Using the Results of Physics Education Research," UniServe Science News 13 (1999)
17. Hausfather, S., "It's Time for a Conceptual Change," *Science and Children*, Nov/Dec, 22 (1992)
18. Thomas, M.F., I. Malaquas, M. Valente, and M. Antunes, "An Attempt to Overcome Alternative Conceptions Related to Heat and Temperature," *Physics Education*, **30**(1), 19 (1995)
19. Thacker, B., K. Eunsook, K. Trefz, and S. Lea, "Comparing Problem Solving Performance of Physics Students in Inquiry-Based and Traditional Introductory Physics Courses," *American J. Physics*, **62**(7), 627 (1994)
20. Prince, M., M. Vigeant, and K. Nottis, "Assessing the Prevalence and Persistence of Engineering Students' Misconceptions in Heat Transfer," *J. Eng. Ed.*, **101**(3), 412 (2012)
21. Miller, R., R. Streveler, B. Olds, and J.D. Slotta, *Thermal and Transport Concept Inventory* <http://www.thermalinventory.com/surveys.html> 2011
22. Nottis, K., M. Prince, and M. Vigeant, "Building an Understanding of Heat Transfer Concepts in Undergraduate Chemical Engineering Courses," *US-China Education Review*, **7**(2), 1 (2010)
23. Prince, M., and M. Vigeant. "Using Inquiry-Based Activities to Promote Understanding of Critical Engineering Concepts," Paper presented at the American Institute of Chemical Engineers National Conference, San Francisco (2006)
24. Prince, M., M. Vigeant, and K. Nottis, "A Preliminary Study on the Effectiveness of Inquiry-Based Activities for Addressing Misconceptions of Undergraduate Engineering Students," *Ed. for Chemical Engineers*, **4**(2), 29 (2009)
25. Lewis, E.L., and M.C. Linn, "Heat Energy and Temperature Concepts of Adolescents, Adults and Experts: Implications for Curricular Improvements," *J. Research in Science Teaching*, **40**(S1), 155 (2003)
26. Streveler, R., B. Olds, R. Miller, and M. Nelson, "Using a Delphi Study to Identify the Most Difficult Concepts for Students to Master in Thermal and Transport Science," Proceedings ASEE Annual Conference, Nashville, TN (2003)
27. Jacobi, A., J. Martin, J. Mitchell, and T. Newell, "A Concept Inventory for Heat Transfer," Proceedings Frontiers in Education Conference, Boulder, CO (2003)
28. Omar, N., R. Zulkifli, and R. Hassan, "Development of a Virtual Laboratory for Radiation Heat Transfer," *European J. Scientific Research*, **32**(4), 562 (2009)
29. Miller, R. 2008. Human Thermometer Model Eliciting Activity. <http://www.modelsandmodeling.net/Thermodynamics_and_Heat_Transfer_files/Human_Thermometer_MEA_part_1_and_part_2_FINAL_VERSION_1.pdf>
30. Shuman, L., M. Besterfield-Sacre, B.P. Self, R. Miller, T. Moore, J. Christ, E. Hamilton, B. Olds, and H. Diefes-Dux, "Special Session: Next Generation Problem-Solving: Results to Date—Models and Modeling Using MEAs," Proceedings ASEE Annual Conference, Louisville (2010)
31. Bergman, T.L., A.S. Lavine, F.P. Incropera, and D.P. DeWitt, *Introduction to Heat Transfer*, 6th ed. New York: Wiley, 2011
32. Prince, M., M. Vigeant, and K. Nottis, "The Use of Inquiry-Based Activities to Repair Student Misconceptions Related to Heat, Energy, and Temperature," Proceedings ASEE Annual Conference, Vancouver, B.C. (2011)
33. Fraenkel, J.R., N.E. Wallen, and H.H. Hyun, *How to Design and Evaluate Research in Education*, 8th ed. New York: McGraw Hill (2012) ❐