

ENGINEERING DESIGN AND CONCEPTUAL CHANGE IN SCIENCE: ADDRESSING THERMAL ENERGY AND HEAT TRANSFER IN EIGHTH GRADE

Abstract: The purpose of this research was to investigate the impact of engineering design classroom activities on middle school students' conceptions of heat transfer and thermal energy. One eighth-grade physical science teacher and the students in three of her classes participated in this mixed-methods investigation. One class served as the control receiving typical instruction. Students in a second class had the same learning objectives, but were taught science through an engineering design curriculum that included demonstrations that targeted specific alternative conceptions about heat transfer and thermal energy. A third class also used the engineering design curriculum, but students experienced typical demonstrations instead of targeted ones. Conceptual understandings of heat transfer and thermal energy and attitudes toward engineering were assessed prior to and after the interventions through interviews, observations, artifact analysis, a multiple choice assessment and a Likert scale assessment. Results indicated that the engineering design curriculum with targeted demonstrations was significantly more effective in eliciting desired conceptual change than the typical instruction and also significantly more effective than the engineering curriculum without targeted demonstrations. Implications from this study can inform how teachers should be prepared to use engineering design activities in science classrooms for conceptual change.

Christine G. Schnittka, University of Kentucky

Randy L. Bell, University of Virginia

Introduction

One important goal of science education is to feed the research pipeline with a steady supply of scientists and engineers that will tackle the global 21st century issues we face, i.e. energy shortages, environmental decline, climate change, natural resources, nutrition, and world health (Trefil, 2008). Perhaps even more important is the goal of current reforms to increase scientific and technological literacy for all, not just for future scientists and engineers.

In order to promote scientific and technological literacy, reform efforts in science education stress a change in emphasis toward active, inquiry-based learning (AAAS, 1993; NRC, 1996). The active process of learning involves both mental activities and physical activities as students work with their teachers and peers and interact with the learning environment (Bryson & Hand, 2007; NRC, 1996). While engaged in active learning, students can make gains in content knowledge, scientific process skills, and attitudes towards science. In general, active learning reaches students who possess a wide variety of learning styles, much more so than traditional teaching and learning as students think about and perform meaningful activities (Bransford, Brown, & Cocking, 2000).

However, even with active, inquiry-based learning, students and adults alike have a difficult time understanding many scientific explanations of natural phenomena (Brown, 1992; Clement, 1993; Driver, Guesne, & Tiberghien, 1985; Driver, Squires, Rushworth, & Wood-Robinson, 1994; Vosniadou & Brewer, 1992; Wandersee, Mintzes, & Novak, 1994). This is an obvious obstacle

to scientific literacy. People may hold onto their own invented theories for a lifetime. In order for conceptual change to take place, a learner must become dissatisfied with his alternative conceptions, then grasp an intelligible new conception and use that conception to solve a problem (Posner, Strike, Hewson, & Gertzog, 1982). Many methods for helping students with conceptual change in science have been implemented, some more successfully than others. With the current and popular integration of Science, Technology, Engineering, and Mathematics (STEM) in K-12 curricula, some have suggested that engineering design could facilitate desired conceptual change in science and have attempted to design curriculum to do so (Fortus, Dershiimer, Krajcik, Marx, & Mamlok-Naaman, 2004; Kolodner et al., 2003).

Since the Sputnik era, universities and professional organizations have developed dozens of engineering education programs for pre-college students to help them understand what engineers do, teach them about the engineering design process, and target deficits in scientific and technological literacy. However, there is a paucity of research on how effective these programs are at helping students actually learn important science concepts (Chaker, 2008), and there is virtually no research on how engineering design activities might promote conceptual change in science. Recent studies have shown that students engaged in engineering design activities do not implicitly learn science concepts at all (Blumenfeld et al., 1991; McRobbie, Stein, & Ginns, 2000; Silk, Schunn, & Cary, 2007). Design-based science instruction does help students integrate abstract thinking into concrete applications (Roth 1996, 2001). Students can also learn a variety of concepts set into context, such as problem-solving skills (Roth, 1996). In order to help students learn science, teachers must balance managing the design challenge with helping students understand the science concepts related to the design (McRobbie et al., 2000). Time also needs to be set aside for students to share their ideas with each other so that learning is communal instead of competitive, and so that it takes advantage of the benefits of the theoretical framework of social constructivism (Fortus et al., 2004; Hmelo et al., 2000; Puntambekar & Kolodner, 2005).

Theoretical Frameworks

The central features which defined this research were: problem solving through authentic tasks, determining and addressing alternative conceptions, working within social groups, creating tangible artifacts which were meant to represent knowledge (Sadler, Coyle, & Schwartz, 2000), and sideline guidance by a more knowledgeable person- the teacher. These features map neatly to the social constructivism theoretical framework and conceptual change theory.

Social constructivism is a perspective which evolved from the ideas of Soviet psychologist Lev Vygotsky in the early 20th century and Swiss psychologist Jean Piaget in the mid 20th century. Vygotsky stated that “learning awakens a variety of internal developmental processes that are able to operate only when the child is interacting with people in his environment with his peers” (1978, p.90). The social constructivist framework stresses that students play an active role in their own learning, and should work together to solve problems while discussing and debating. The role of the teacher is to determine students’ alternative conceptions, provide concrete sense-making activities which address those conceptions, and facilitate interpretive discussions about the subject. The teacher is a facilitator of learning, and takes an active role in interacting with students to find out what they know and what they are thinking. Knowledge is constructed by the individual, but mediated through social interactions with peers and the teacher in the classroom (Palinscar, 1998; Tobin & Tippins, 1993).

Papert (1980) described artifacts as “objects to think with” because they help bring abstract concepts into the concrete and tangible realms. When artifacts are shared and critiqued by others, students use them to reflect on what they know (Krajcik & Czerniak, 2007). Designed and created artifacts can free up mental resources for developing more complex ideas (Roth, 2001). In design-based science activities, the artifact is the central focus where every component of the designed device is supposed to serve a real purpose and reflect some scientific knowledge.

Additionally, it has been shown that when students have greater interest in what they are learning, they will process information at deeper levels (Brophy, 1998; Schiefele, 1991; Hidi, 1990). Problem solving and design tasks that relate to students’ lives should be the catalyst to increase student interest and promote deeper conceptual knowledge.

For the past three decades, research has demonstrated that people have deeply rooted beliefs, or alternative conceptions, about how the world works, and these beliefs commonly contrast with current scientific views (Duit & Treagust, 2003). The conceptions are creative and useful to a child as he or she navigates the practical world, and must be respected as such, but teachers need to be aware of their students’ alternative conceptions and focus on helping their students restructure them (Brown, 1992; Clement, 1993). Alternative conceptions are resistant to change as people are usually very reluctant to discard their long-held beliefs. When people come to a point where they are dissatisfied enough with their initial conception to adopt a new, more scientific one, conceptual change occurs. The science education literature is replete with strategies for teachers to identify, target, and help students work through their alternative conceptions (Posner, Strike, Hewson, & Gertzog, 1982).

One way to address alternative conceptions is through experiencing concrete, understandable, believable, explicit, and visual examples (Brown, 1992). Another effective method is through the use of experimental lessons and demonstrations which can serve as bridging analogies (Clement, 1993).

The theoretical framework of the conceptual change model informs educators how to best address students’ alternative conceptions in science. The learner must become dissatisfied with existing conceptions in order to discard or modify them. The new conception presented must be intelligible to the learner. The new conception must be plausible. It also must possess the ability to solve problems consistently, and finally, the new concept must have the potential to help the learner pose new questions about the phenomenon (Posner et al., 1982). Hewson and Hewson (1983) speculate that the first phase of conceptual change takes place as new concepts are integrated with existing ones. Following this is differentiation, where existing conceptions are defined and differentiated from more scientific ones. Finally, there is an exchange of old conceptions for new ones as students recognize that their old conceptions are not plausible and their new conceptions are more explanatory. The student can then link the new conceptions with their experiences.

The theoretical frameworks of social constructivism and conceptual change provided a lens with which to view this research, and a means with which to collect and analyze data.

Purpose

The purpose of this study was to better understand how middle school students could learn significant science concepts at a deep conceptual level through an engineering design challenge that encouraged the application of scientific understandings. This study investigated how

engineering design activities could be used to target standards-based science concepts and promote conceptual change. Three treatment variations were presented: one being an engineering design curriculum with activities embedded to target students' alternative conceptions, one being the same engineering design curriculum without targeting alternative conceptions, and the third being typical instruction without engineering design. Without explicitly addressing alternative conceptions, it was hypothesized that engineering design alone would not be enough to promote conceptual change in science. The major research questions were:

1. What are students' conceptions about thermal energy and heat transfer before instruction?
2. How do students' conceptions about thermal energy and heat transfer change after instruction?
3. How do the three instructional approaches compare in promoting conceptual change?

The research questions are well suited to the theoretical framework of social constructivism because they address sense-making and elucidation of alternative concepts through social group activities and teacher scaffolding.

Methods

This mixed-methods study examined one teacher and her three classes of eighth grade students ($n = 71$) in a suburban public school in the Mid Atlantic region of the United States. Students worked in small collaborative groups on activities centered on the science of thermal energy and heat transfer. Each class received one of three treatments. The engineering treatment in this study, the design-based science curriculum called *Save the Penguins* Engineering Teaching Kit (ETK) was developed at the University of Virginia through the Virginia Middle School Engineering Education Initiative (VMSEEI) (Schnittka, in review). This curriculum is one of dozens created by members of the VMSEEI in order to expose middle school students to engineering design through their regular science and math classes. In the *Save the Penguins* curriculum, students were challenged to create a dwelling that reduced heat transfer in order to keep a penguin-shaped ice cube from melting. Students worked in peer-mediated groups, and played an active role in their learning as they solved problems and cooperated on the design and testing of the device.

Participants

The three classes in this study were statistically equivalent in terms of their state math and reading scores from seventh grade. A coin toss was used to determine which of the classes would receive the variations of the treatment.

The first class (hereby referred to in this paper as the ETK class) consisted of 21 students: 9 male and 12 female. All students were Caucasian except for one female of Hispanic ethnicity and one male of South Asian ethnicity. The second class (referred to as the Control class) consisted of 27 students: 17 male and 10 female. All students were Caucasian. The third class (always referred to in this paper as the **ETK+D** class) consisted of 23 students: 12 male and 11 female. Seventeen students were Caucasian, two boys and one girl were of Asian ethnicity, one girl was of South Asian ethnicity, one boy was African American, and one girl was African American. This was the most ethnically diverse class in the study.

The teacher in this study had 4 years of full-time middle school science teaching experience. She was working part-time on a Master's degree in educational leadership at the time of this study, had experience as a science department chair, and was certified to teach middle school science in three states. She was an enthusiastic teacher, interested in cooperative learning, student motivation, integrating life and physical science instruction, and had experience using design as an instrument to facilitate teaching physical science concepts.

Site

This study took place at Montebello Middle School¹, a rural public school in a Mid-Atlantic state. It is the largest middle school in a county with approximately 100,000 citizens. Data published for the 2006 school year² reported that with 747 students, 89.6% were Caucasian, 4.3% were African American, less than 2% were Asian American, and 2.1% were of Hispanic ethnicity. During the 2006 school year, 10.6% of students were eligible for free or reduced lunch. Montebello Middle School is located in the rural countryside between a medium-sized city and a small county town. Its students feed from four rural elementary schools; two of these schools are considered to be in affluent areas of the county while two are not.

Treatments

Students in all three classes were taught about thermal energy and heat transfer with the same learning objectives, the same homework assignments and journal prompts, and the same end-of-unit test. The unit took six 80 minute class periods to complete. In order to insure treatment fidelity and equivalent opportunities to learn the science concepts, all three classes were observed daily throughout the study, and observations were discussed with the teacher daily. Two major differences existed between classes- the design activity and the targeted demonstrations. Students in the ETK class were taught science through engineering design with the *Save the Penguins* curriculum, but without five demonstrations that specifically targeted students' alternative conceptions about thermal energy and heat transfer. Students in the Control class were taught the same science learning objectives through the teacher's typical instruction, an inquiry-based, active-learning curriculum the teacher used the previous year. Students in the **ETK+D** class were taught science through engineering design with the *Save the Penguins* ETK, but they also experienced five targeted demonstrations developed for this study. Figure 1 illustrates the three treatment classes and activities that were conducted during the six class periods.

¹ All personal names and place names are pseudonyms.

² Data reported in the latest annual progress report for the county.

Day	ETK Class	Control Class	ETK+D Class
1	Discuss caloric, heat, heat transfer. PowerPoint about engineering. Discussion of engineering.	Discuss caloric, heat, heat transfer. PowerPoint on thermal energy. Discuss methods of heat transfer and examples. Students make books on heat transfer. Students watch video on heat.	Discuss caloric, heat, heat transfer. PowerPoint about engineering. Discussion of engineering. Cans demonstration.
2	Discuss heat and temperature. Balloon demonstration. Demo with beakers of hot and ice water. Demo of food coloring in different temperatures of water. Students make storyboards about heat transfer.	Discuss heat and temperature. Balloon demonstration. Demo with beakers of hot and ice water. Demo of food coloring in different temperatures of water. Students conduct a phase change lab in groups.	Discuss heat and temperature. Discuss cans demonstration. Trays demonstration. Spoons demonstration. Students make storyboards about heat transfer.
3	Discuss how a thermos works. Watch video on heat. Introduce design challenge. Test materials.	Discuss how a thermos works. Computer lab research time on building materials or clothing that prevents heat transfer.	Discuss how a thermos works. House demonstration. Mylar demonstration. Introduce design challenge. Test materials.
4	Discuss insulators and metals. Test materials and share results.	Discuss insulators and metals. Students work on posters about their research.	Discuss insulators and metals. Test materials and share results.
5	Students build houses and test them.	Students work on posters. Students complete a computer simulation activity on conduction.	Students build houses and test them.
6	Students discuss designs and re-build and re-test. Students take posttests.	Students work on vocabulary for end of unit preparation. Students take posttests.	Students discuss designs and re-build and re-test. Students take posttests.

Figure 1. The three treatments

Targeted demonstrations

One targeted demonstration in the **ETK+D** class had students predicting which material, wrapped around a can of soda, would keep it cold the longest. This demonstration targeted students' alternative conceptions that aluminum foil "traps coldness" and wool socks warm things. Another demonstration had students observe ice cubes placed in plastic and metal spoons they held and predict which one stay frozen longest. This demonstration targeted students' alternative conception that metals are naturally colder than plastics, and would therefore keep an ice cube frozen longer. Other demonstrations involved a cardboard house with a black painted roof under a heat lamp with thermometers in the attic and first floor spaces. The house was heated, temperatures were measured, and students predicted what would happen when the house was flipped upside down. This demonstration targeted student's alternative conception that heat is a substance that rises, and helped students visualize the hot air rising, not "heat." In a final demonstration, aluminized Mylar material was draped over a student's hand under a heat lamp, and the student made observations and inferences. This demonstration targeted students' alternative conception that shiny objects "absorb heat." Together, these demonstrations took approximately one class period.

Typical demonstrations

Students in the Control class and the ETK class the other two classes participated in demonstrations which the teacher typically used to illustrate convection, conduction, radiation, and thermal energy. She showed students food coloring in three different temperatures of water and had them explain the differences. She had students measure and graph the temperature of an ice bath as it heated on a hot plate to boiling. She placed balloons in the freezer and left some at room temperature for students to observe and make inferences from. She showed a video with demonstrations about heat and temperature that could not be performed in the classroom. These typical demonstrations illustrated methods of heat transfer, but did not specifically target any particular alternative conceptions students might have about heat transfer and thermal energy.

Engineering design challenge

The *Save the Penguins* engineering design challenge presented to the ETK and **ETK+D** classes began with a scientific inquiry as students tested materials with which to build a dwelling for the penguin-shaped ice cube to keep it from melting in a test oven. Students were provided with materials such as felt, foam, cotton balls, paper, shiny Mylar, and aluminum foil to test for their effectiveness at preventing some form of heat transfer. Students compared materials under a shop light mounted to a ring stand, shining on a black surface. Students had access to thermometers and timers to fairly test samples under the light or on the hot black surface. As students explored the materials, they began to formulate ideas about how to build their dwelling for the ice cube so that the least amount of ice melted. All materials were priced and "sold" to students who worked within the constraint of a budget. They were able to purchase materials after testing them and deciding which ones were better building materials.

Testing the Design

Students had the opportunity to elaborate on the knowledge they gained from the demonstrations, discussions, and testing when they got out their scissors, tape and glue, and took on the role of engineer as they purchased materials, designed, and built their dwellings. Students conducted further testing, discussed results with other groups, and received support for their ideas from the teacher and peers. The carefully created and frozen 10 gram ice penguins were placed inside the individual dwellings and then simultaneously placed in the oven and subjected to 20 minutes of intense radiation, convection, and conduction (See Figure 2).



Figure 2. Little dwellings in the oven.

The oven was a large plastic storage bin lined with aluminum foil on four sides and spray-painted black on the bottom with three 150W shop lights shining inside so that all three forms of heat transfer could occur. Houses placed in this pre-heated oven experienced conduction with and radiation from with the black floor, radiation from all sides, and convection as hot air rose off the black bottom. After testing, students discussed which design features were best at preventing conduction with the black oven bottom. Which design features were best at preventing radiation from the heat lamp from penetrating the dwellings? Which design features were best at preventing the convection of hot air moving? The students discussed and decided. They analyze the results, and then went back to the drawing board to make revisions and improvements.

Students were able to use their communal shared results and ideas to make revisions that help save even more ice penguin. Each group of students was a winner if their revised design was better than their first one. Just as engineers continually work together in an iterative process to make things better, so the middle school engineers did the same.

Data Collection and Analysis

A variety of data sources were used to determine how students were learning about science and possibly engineering in the three classes. These data sources included daily observations of all classes, formal interviews with a subset of students prior to and after instruction, formal and informal interviews with the teacher, and all participant-created artifacts. Although data regarding engineering knowledge and attitudes were collected and analyzed, in this paper, only data concerning science understandings will be addressed.

Observations

Daily classroom observations of all three treatments were made by the first author. They were videotaped from the back of the room with an on-board microphone and a wireless lavalier microphone on the teacher. All videos were transcribed for analysis. A total of 18 observations of 80 minutes each were made during the intervention, and a total of 15 observations of 80 minutes each were made prior to the intervention in order to familiarize the students with the presence of an observer and video camera. Observations were a primary source of data for characterizing how the students interacted with the different curricula, interacted with the teacher, and interacted with each other.

Pre and Posttests

All participants completed a 12-item multiple choice Heat Transfer Evaluation (HTE) pretest two weeks prior to instruction, and as a posttest immediately following the intervention. See Appendix A for HTE instrument. The purpose of administering this instrument was to identify alternative conceptions students possessed about heat transfer and thermal energy, and compare differences between classes and between times it was administered. Prior to this study, the HTE instrument underwent extensive evaluation of reliability and face, content, and construct validity and was found to be both reliable and valid for this study (Schnittka, 2009). Face and content validity were ascertained by a panel of 8 experts in the field of physical science education who reviewed the instrument to determine if it sufficiently tested the content of heat transfer and the objectives of the ETK. The assessment was modified according to the panel's suggestions, and further rounds of review and modification took place until 100% agreement was attained for wording and inclusion of each test item. To assess construct validity, 59 eighth graders in a pilot study, 65 engineering students who had taken coursework in heat transfer and thermodynamics, and 31 university students not pursuing science or engineering degrees took the test in mid-April, 2008. Their results were compared with separate Mann-Whitney tests of statistical significance because not all data sets were normally distributed. Construct validity was assumed because engineering students correctly answered a statistically significant and substantially larger number of questions than the other university students. On this 12-point test, engineering students' scores had a mean of 10.47 (Mdn = 11) and, other university student scores had a mean of 6.84 (Mdn = 7), a difference significant at $p < .001$ with an effect size $r = .62$. The test-retest method was used to establish reliability for the 12-item Heat Transfer Evaluation. A group of 54 eighth grade students at a different school studying history and not science, took the test once during the first week of April, 2008, and again 2 weeks later. Linear regression was used to determine that the correlation coefficient was $R = .71$. The students' test mean the first

time was 4.54 points out of 12, and the students' test mean the second time was 4.44 points out of 12. The primary alternative conceptions addressed in the HTE were:

1. Cold moves from cold places to warmer places.
2. Insulators keep cold out and/or generate heat.
3. Lighter colored clothes keep you cooler because they let more air in.
4. Metals attract heat.
5. Heat rises.
6. Aluminum foil is a good insulator for cold things.
7. Heat moves because it builds up in once place which cannot hold it.
8. Metals are naturally colder than non-metals.
9. Light colored or shiny objects absorb radiation.

Students were also administered a survey of attitudes toward engineering prior to and after instruction. This survey was used to determine students' perceptions of the role engineers play in society, and determine their own personal interest in engineering as a career possibility. The Attitudes Toward Engineering Survey (ATES) was also found to be both reliable and valid for this study after extensive evaluation (Schnittka, 2009). The topic of engineering attitudes and the impact of the interventions on attitudes toward engineering is not the focus of this paper.

Interviews

A representative subset of students from each class was interviewed prior to and after the interventions. Eight students from the ETK class, 10 students from the Control class and 11 students from the **ETK+D** class volunteered for interviews. Students self selected for interviews, but in order to make sure that the interviewed students represented each class as a whole, their pretest scores on the HTE were compared. Means were 4.38 out of 12 for the ETK students, 4.9 for the Control students, and 4.1 for the **ETK+D** students. Each sample equally represented a distribution of students who scored high, middle, and low on the heat transfer evaluation pretest. Interviewed student pretest scores on the HTE were statistically equivalent ($p = .715$, effect size $r = .11$). See Appendix B for student entrance interview protocol and Appendix C for student exit interview protocol. The teacher was formally interviewed prior to the interventions, informally throughout the duration of the study, and formally at the conclusion of the study. All interviews were audiotaped and transcribed for analysis.

Additionally, designed artifacts, homework assignments, and classwork assignments were analyzed for additional information about students' learning, and were used as prompts during interviews.

Results

Pre-Instruction Results

Prior to instruction, participants in all three treatment groups had similar conceptions about heat transfer and thermal energy. The ETK class mean was 4.33 out of 12 possible points, the Control class mean was 4.63 and the **ETK+D** class mean was 4.09. Classes were statistically

equivalent on the HTE pretest ($p = .601$) with an effect size $r = .09$. These scores were slightly better than chance. See Figure 3 for box plots representing pretest scores for each class.

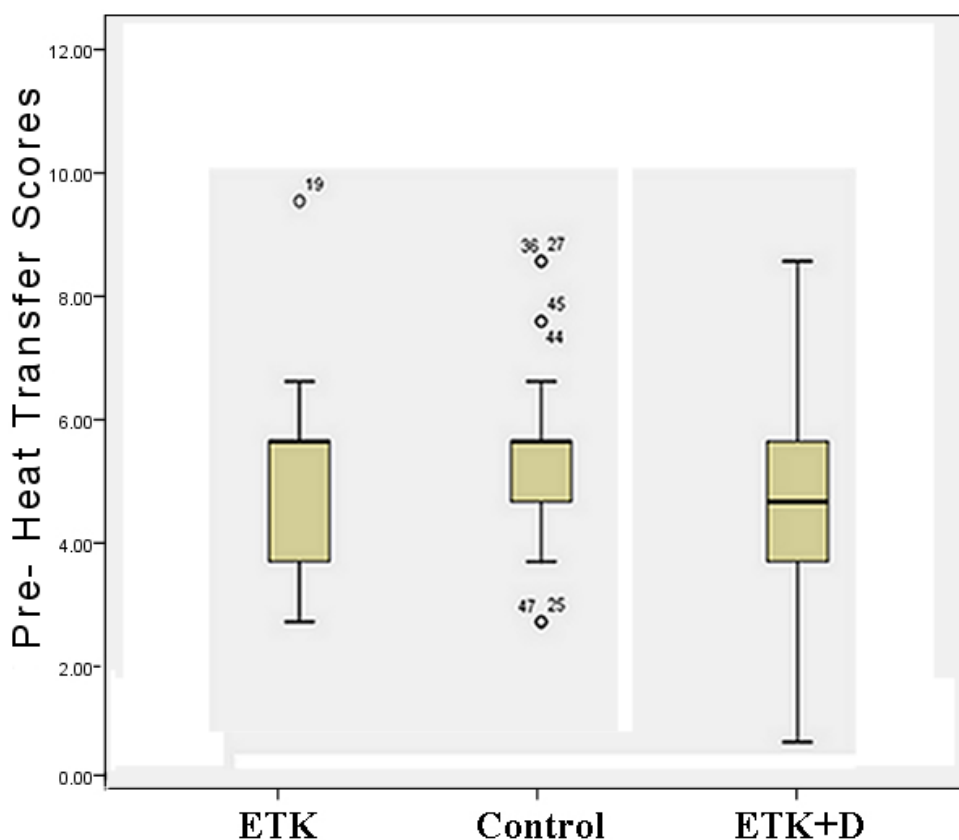


Figure 3. Box plots representing HTE pretests for each class.

Prior to the interventions, students were familiar with everyday experiences with heat and temperature, such as body heat. Few students understood the relationship between thermal energy and the motion of molecules and the friction between molecules. Students often articulated that metals absorbed cold, imagining cold to be some sort of substance that flowed, getting trapped and absorbed like heat. Jim was typical in stating that, “So if you like, have a cup of water you put in the freezer, then the cold air from the freezer gets the water and makes it into an ice cube.” (Jim, Control class, entrance interview)

These conceptions about heat and temperature seemed to come from students’ personal experiences with staying warm, getting burned, and feeling cold in their everyday lives. In order to make some sense of their world, they developed their own theories, their own alternative conceptions. On average, there were twice as many alternative conceptions expressed by students in all classes as there were scientific conceptions. The most common alternative conceptions expressed were:

1. Cold transfers from cold to warm
2. Insulators generate heat

3. Insulators are warm, metals are cold
4. Insulators keep cold from transferring
5. Metals trap or absorbs cold
6. Heat is always warm or hot
7. Heat and temperature are equivalent
8. Heat always rises
9. Dark objects attract heat

As examples of how students expressed these conceptions, Sarah, a student in the ETK class illustrated conceptions 6 and 8 by stating: “Like if it’s snowing, it’s not going to have heat, or if you are underground it’s cooler because heat rises up” (Sarah, ETK class, entrance interview). Jim, a student in the Control class illustrated alternative conception 1 by stating: “So if you like, have a cup of water you put in the freezer, then the cold air from the freezer gets the water and makes it into an ice cube” (Jim, Control class, entrance interview). Sarah, a student in the ETK class illustrated concepts 2 and 3 in the following discussion: The following interview excerpt illustrates concepts 2 and 3:

Researcher: So if you put a sweater on a counter, would the counter get warm or would the sweater get warm by itself?

Sarah (ETK class, entrance interview): The countertop would be warmer.

Researcher: Would the sweater itself generate heat?

Sarah: The bottom of the sweater, the one laying on the countertop would.

During-Instruction Results

Based on observations, interviews, and data collection, students acquired knowledge about heat transfer and thermal energy through different activities, and to different degrees during the intervention. Posttests and exit interviews were used after the intervention to help determine how students’ conceptions changed depending upon which intervention they received.

The following excerpt is from day 4 of the unit in the ETK class as students and teacher discussed materials available for purchase. Since students did not have the targeted demonstrations to refer to, they were using information from their materials testing to make design decisions:

Teacher: Next thing, you're going to have to think about building your igloo. You have to think about radiation coming from where?

Students: The lamps.

Teacher: We're going to have the heat lamps turned on ahead of time. Is there conduction? Is there convection? Yep. There are three things you have to think about. What was a good thing to reflect radiation?

Reggie: Mylar and aluminum foil.

Teacher: What about to insulate?

Kate: Bubble wrap.

Students demonstrated a basic understanding of radiation and insulation. As students in this class were re-designing their dwellings on day 6 of the intervention, they were still making use of the knowledge they gained from the materials testing. The following excerpt is from a

discussion that one student group in the ETK class was having while trying to re-design their dwelling for the second test in the hot oven. They had determined they would use paper as a building material, and were debating which color to use. They had previously tested sample pieces of colored paper under shop lights.

Margaret: That's a dark color, it will attract heat.

Daniel: I think white paper.

Margaret: Yeah, white paper.

Reggie: We need to do something to give it more shade.

Daniel: I don't think we have enough materials to build shade.

The students were thinking about the materials in terms of which ones were affordable, within their given budget to purchase supplies, which ones would provide shade from the radiation, which ones would reflect radiation, and which ones were good insulators. They made creative use of the less expensive materials available to them, they discussed air as a good insulator, used a reflective material on the bottom of the dwelling to reflect radiation from the black floor, used light colors instead of dark ones, and reduced conduction by raising the dwelling off the floor.

Students in the ETK class were not using many scientific terms in their group discussions as they designed and built the dwellings. While they were assigned textbook readings for homework, their class activities were mostly in peer groups, and their knowledge was primarily socially constructed in those groups.

Students in the Control class learned in social groups as well during several activities, but there was a greater emphasis on teacher-centered transmission of knowledge. On day 1 of the unit, the teacher was delivering a PowerPoint presentation with slides containing definitions and images representing thermal energy and heat. She did not give students many opportunities during this didactic lesson to discuss the concepts, and often answered her own questions.

Teacher: Talking about thermal energy and heat, these can be a little confusing. Thermal energy is the total amount of energy in an object. Heat is defined as the movement of those particles or energy from a higher temperature to a lower temperature. It is heat a liquid or gas? It is an energy. So heat is always going from a warmer region to cooler one. Can it ever reverse?

Student: No.

The teacher did not always correct students' alternative conceptions during class discussions, as illustrated in this excerpt from later on in the first day of the unit:

Teacher: When you're talking about convection, you're talking about liquid or gas moving. It's like a pot boiling. What's going to heat up first?

Student: Water.

Teacher: What part of the water?

Student: The top. (The teacher does not correct this statement)

Teacher: What happens as the water heats up?

Student: Heat rises (The teacher does not correct this statement)

Teacher: And then it keeps going in that cycle.

The conversations in the Control class were more authoritative than dialogic, and whereas students in the ETK class were working together to solve problems and use the concepts of heat and energy in a design, students in the Control class were learning terms and definitions. Often they were learning concepts incorrectly as the teacher did not respond to their comments revealing alternative conceptions.

Students in the **ETK+D** class performed the same tests on materials, and constructed the same types of dwellings for penguin-shaped ice cubes as students in the ETK class. However, they faced cognitive dissonance when shown five targeted demonstrations. They then referred back to these demonstrations in their discussions. Students in the **ETK+D** class made the most significant positive changes in scientific understandings during the intervention compared to students in the Control class and the ETK class. When students in the **ETK+D** class began designing their penguin dwelling, one group was debating what to wrap the ice cube with. Stacey was able to apply her knowledge about metals to the design of the dwelling.

Stacey: Maybe we can wrap the penguin with wax paper.

Samantha: We're going to wrap in aluminum foil

Stacey: But that's a conductor. It conducts heat.

Students who did not have the complete **ETK+D** curriculum held onto the idea that metals kept in coldness, trapped cold, were colder than other materials, attracted and absorbed cold. Very few students in the **ETK+D** class had these conceptions. If they had, they would have wrapped their ice cube in metal to keep it cold.

Many students articulated that hot air rises during the interventions, however the **ETK+D** class made the most gains in understanding that it is hot air, not "heat" as a substance that typically rises. However, there was discussion among the students in both design classes about how hot air would be rising off the black bottom of the test oven, and how they had to seal their dwelling from this hot air. Students in the **ETK+D** class also articulated with greater frequency how conductors can take heat away from your body if you touch them. This is most likely due to the demonstration with the spoons and the trays, and the discussion afterwards about how "cold" does not move into the hand, but heat from the hand moves into the spoon and melts the ice cube. However, students in all classes had experiences with a lab or demonstrations involving ice melting. A group of students in the ETK class realized that simply touching and placing their penguin ice cube in the dwelling would cause some of it to melt, and decided to pick it up with bubble wrap to prevent heat from transferring to the ice cube.

Students made positive gains in their understandings of insulation during all three interventions, but especially in the **ETK+D** class. Students in the **ETK+D** class had many scientific conceptions about insulation, whereas the other classes had fewer scientific conceptions. The statements that wood is an insulator, that a vacuum is a better insulator than air, that air is a good insulator, and that plastic is a good insulator were made by students in the **ETK+D** class more frequently than students in the other two classes. If this is due to their experiences with insulating materials in the construction of the penguin dwellings, why was there a difference between the two engineering design classes? Perhaps the demonstration with the cans covered in different materials made a lasting impact that helped them understand the insulating properties of the building materials better.

Post-Instruction Results

Figure 4 illustrates the median, quartiles, and range of scores on the HTE posttests for each class.

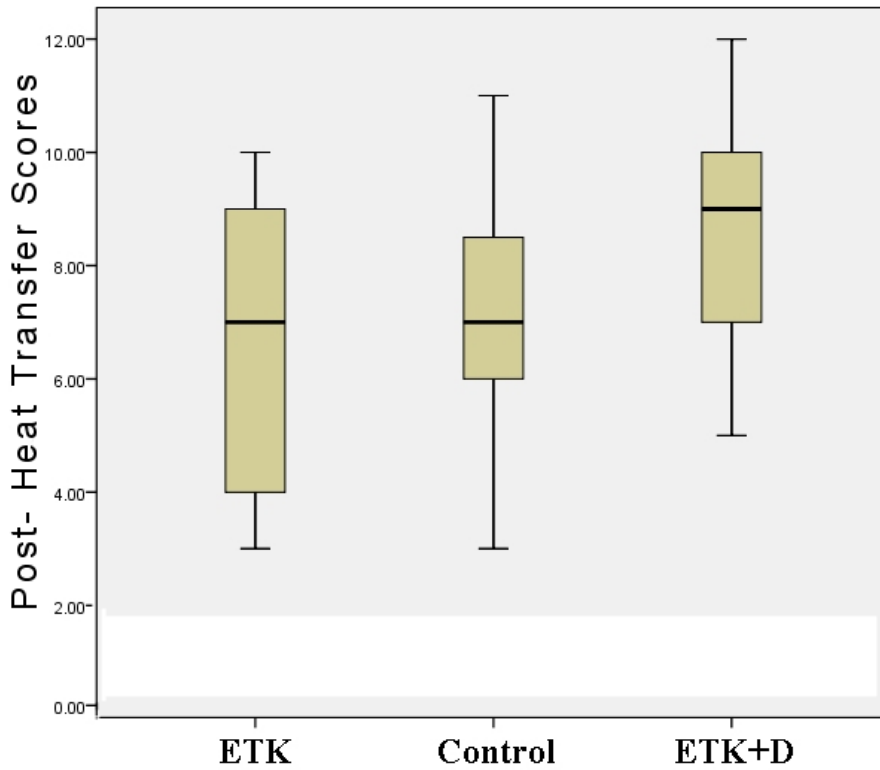


Figure 4. Box plots representing HTE posttests for each class.

In all three classes, the gains from pre- to posttest on the HTE were statistically significant ($p < .001$). However, an ANCOVA using the pretest score as the covariate demonstrated that the classes were not statistically equivalent in terms of their change in heat transfer knowledge across time $F(2,67) = 6.549, p = .003$, with an effect size of $r = .29$. There was a significant difference between the **ETK+D** class scores and both the ETK class scores and the Control class scores. There was no significant difference between the ETK class scores and the Control class scores. See Table 1 for means. Figure 5 illustrates the interaction between classes on the HTE score means.

Table 1
Pre and posttest means and standard deviations on the HTE

	Pretest	Posttest
ETK Class ($n = 21$)	4.33 ($SD = 1.83$)	6.43 ($SD = 2.52$)
Control Class ($n = 27$)	4.63 ($SD = 1.64$)	7.19 ($SD = 1.84$)
ETK+D Class ($n = 23$)	4.09 ($SD = 1.81$)	8.22 ($SD = 1.94$)

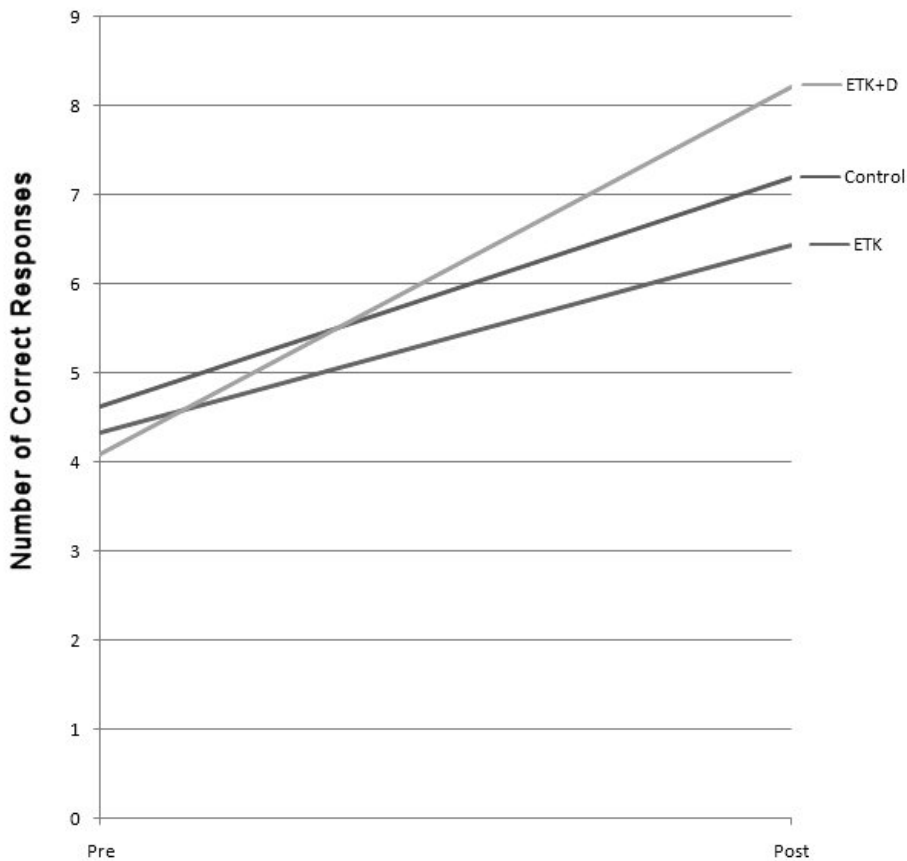


Figure 5. The interaction between class scores on the HTE pre and posttest

Based upon HTE posttests and exit interviews, students in the **ETK+D** class made more gains in understanding heat transfer and thermal energy than students in other classes. Students in the **ETK+D** class had a better understanding that heat can be transferred from room temperature or even cold objects as long as the heat is moving to an area with a lower temperature. Fewer students in the **ETK+D** class expressed alternative conceptions, such as “heat rises” and “cold transfers.” Students in the **ETK+D** class understood insulators and conductors better. They were also able to better apply their knowledge to new situations.

When compared with the list of alternative conceptions that students articulated during entrance interviews, each class made positive gains in reducing the number of alternative conceptions held about heat and energy. Students in the **ETK+D** class articulated 12 alternative conceptions during interviews after the intervention, while students in the ETK class articulated 21, the greatest number of alternative conceptions after intervention.

Exit interviews were conducted with a representative sample of students from each class, many of them the same students who had participated in entrance interviews. Diana, a student in

the **ETK+D** class was able to correctly answer the question, “Why is it cold on the countertop underneath a can of cold soda?”

The countertop was warmer than the soda and so the heat from the countertop traveled into the soda and made the soda warmer but when a substance transfers heat to the colder substance, that substance loses heat so the countertop became colder. (Diana, exit interview, **ETK+D** class)

Students in the ETK class did not modify their typical conception that cold is a substance that travels as much as students in the **ETK+D** class did. Only 52% of students in the ETK class had a scientific conception of “cold” after instruction whereas 72% of students in the **ETK+D** class had a scientific conception. While Jenny was unclear about why ice cubes freeze in a freezer prior to the intervention, she was still unsure afterwards.

I don't know if it's right, but I think when you open the freezer and there's all that cold air, I still think that the ice just like, it's cause it's so cold, that it just absorbs all of that coldness. I just think that. I don't think I'll ever think differently (Jenny, exit interview, ETK class).

Sakura, a student in the **ETK+D** class was typical of those interviewed in her group, in correctly stating that energy leaves the water in order for it to freeze.

There's no such thing as coldness so the water can't absorb the coldness. The air, it takes the heat out of the water it makes the water have less energy so it becomes a solid. (Sakura, exit interview, **ETK+D** class)

Students in the Control class held approximately the same number of alternative conceptions as students in the ETK class after instruction. The following quote is typical of students interviewed in the Control class.

The water absorbs the coldness from the freezer because the freezer has like a fan in it blowing cold, really cold air and I would think that the water would absorb that and it would turn to ice (Paul, exit interview, Control class).

Summary of Results

Students in the **ETK+D** class were the highest performing after the unit concluded. Not only did they outperform students in the other two classes on the HTE, they stated the fewest number of alternative conceptions about heat transfer during their exit interviews. As evidenced by statements made in their exit interviews, their direct experiences applying their knowledge to the design challenge allowed them to make connections and understand the concepts at a more sophisticated level. Their conceptual understanding, which was aided by the design activity and a set of five targeted demonstrations, allowed them to make better sense of the science and apply it more fully toward the engineering design task. Ten of the 12 penguin dwellings in the **ETK+D** class performed at a satisfactory level (retaining half the mass of the ice cube) whereas only seven designs in the ETK class performed at this level (See Figure 6 for sample dwelling

designs). Perhaps increased understanding of heat and energy allowed students in the **ETK+D** class to do a better job designing and constructing a device to prevent the transfer of thermal energy.

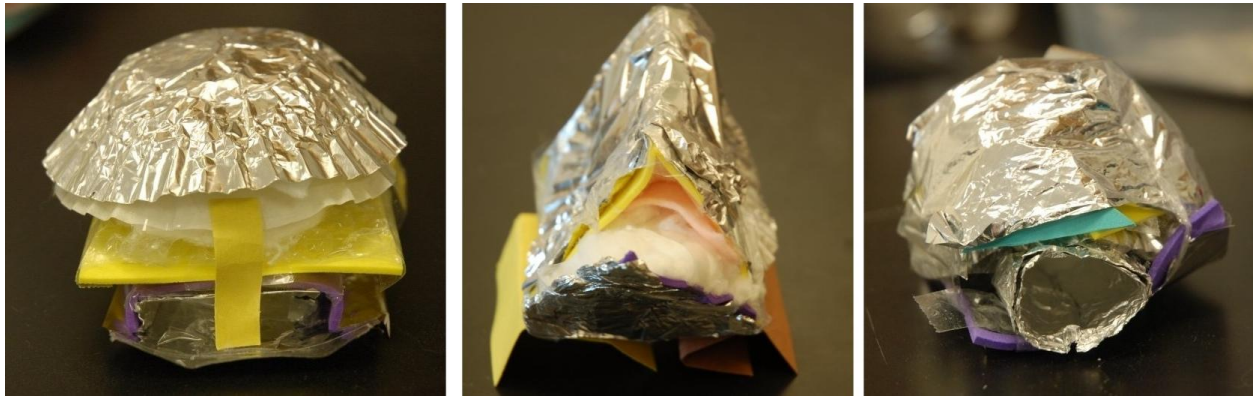


Figure 6. Three sample penguin dwellings

Discussion

The act of designing, conceptualizing, building, and testing a device which relies on blocking heat transfer in order to work, helps students modify alternative conceptions and create more scientific ones. However, when students' alternative conceptions about heat transfer and thermal energy were addressed up front prior to any design or construction of devices, students were able to take a different view on the design task and maximize its potential as a conduit through which to learn science. The design task and the science content appeared to be mutually supportive in the **ETK+D** class. Student groups who designed better dwellings that preserved more ice, performed higher on the HTE posttest. Ironically, in the ETK class, the better the student groups did at building a dwelling that kept the ice cube cold, the worse they did on their HTE posttests. It seems that the design and the science were competing instead of building on each other in the ETK class, like a zero-sum game.

Studies have shown that students engaged in design activities do not implicitly learn science concepts (Blumenfeld et al., 1991; McRobbie, Stein, & Ginns, 2000; Silk, Schunn, & Cary, 2007). Structure is required to bridge the gap between an engineering design problem and the science content which supports it (Puntambekar & Kolodner, 2005). In this study, demonstrations specifically designed to target common alternative conceptions were used to provide that structure for students in the **ETK+D** class. Five targeted demonstrations requiring a total of one class period facilitated student learning. Without addressing alternative conceptions, students doing engineering did not increase their knowledge about heat transfer to the same degree as students in the other classes. These results support those found by other researchers (Penner, Lehrer, & Schauble, 1998; Puntambekar & Kolodner, 2005) who tested for science content gain, but found it lacking when an engineering design activity was used as the primary and sole vehicle for teaching.

This study is unique when compared with all other studies of this type in that it worked within the theoretical framework of social constructivism, used a statistically equivalent control group for comparison, examined science knowledge gains, used the same teacher for all groups, included interviews in all classes prior to and after the interventions to probe for deeper understandings, and utilized a mixed methods approach to data collection and analysis. Because this study included so many robust design features, it was able to produce highly reliable insights

about how engineering design can best be used in the middle school science classroom for conceptual change.

The implication of these results is that some alternative conceptions will persist with an engineering design curriculum that does not explicitly address them, and will also persist with typical instruction. An engineering design intervention that addresses alternative conceptions is more successful in helping students learn science content at a deep conceptual level. Students in the Control class had fewer scientific conceptions than students in the ETK or **ETK+D** class. Students in the **ETK+D** class who were exposed to both the engineering design curriculum and the targeted demonstrations had half the alternative conceptions after instruction when compared with other students.

Implications from this study can inform teachers' use of engineering design activities in science classrooms. These implications are:

- 1) Alternative conceptions will persist when not specifically addressed.
- 2) Engineering design activities are not enough to promote deep conceptual change.
- 3) A middle school teacher can successfully implement an engineering design-based curriculum in a science class.

Future Research

Every investigation has limitations that must be taken into consideration when interpreting the results and implications. In this study, six major limitations were identified which could have compromised the study in some way or another. However, the researcher always made overt attempts to mitigate these limitations. These limitations will be addressed in future research.

Without a fourth classroom to serve as an additional treatment (typical instruction with targeted demonstrations), it was not possible to tease apart the effect of the design and the demonstrations on science conceptual knowledge. Students in the ETK class performed statistically the same as students in the Control class on the HTE. Everything we know about conceptual change indicates that it is not likely that one class period of targeted demonstrations promoted lasting and durable conceptual change (Georghiades, 2000). Perhaps it is possible that the only benefit of the engineering design activity was to enhance understandings about and attitudes toward engineering? Perhaps if the targeted demonstrations had replaced the typical ones, the Control class would have made greater improvement to equal or even surpass that of the **ETK+D** class. The researcher was careful to make sure that all three classes were exposed to interactive demonstrations for the same amount of time, but it is still unknown what role the targeted demonstrations played with regard to the engineering design activity. Perhaps the targeted demonstrations alone did not account for the success, but a combination of the demonstrations and the design activity allowed students to conceptualize heat transfer and thermal energy to a greater and more accurate degree, giving them an advantage over the ETK class. Perhaps this even helped increase their self-efficacy with the design task, and self-efficacy is correlated to achievement (Weisgram & Bigler, 2006). Without an additional treatment group, this inference is not possible. Future research will take this limitation into consideration.

The sample of participants in this study consisted of high-achieving students of low diversity. Although it was ascertained that the three groups were statistically equivalent both in terms of their science and math scores from seventh grade standardized tests, and they were also

equivalent in terms of their knowledge of heat transfer prior to the intervention, the fact remains that the students in this study were all in academically advanced classes. They were primarily white and middle-class. Would engineering design be as effective and well received in a more diverse, less academically-oriented class? The National Assessment of Educational Progress [NAEP] (U.S. Dept. of Education, 2000) reports from the past 30 years indicate that an achievement gap persists in science between students of different genders, ethnicity, and socioeconomic classes. Would this achievement gap narrow with less book-oriented activities and more active ones? Future research will investigate this question.

The results of this study are particular to three classes of students at one school studying one science topic through typical methods and through engineering design. It is worth reiterating that the results cannot be directly generalized to other science content, other age groups, or students of different socioeconomic background. Future research is necessary in order to determine how engineering design coupled with targeted demonstrations may or may not be effective with different age groups, different schools, male teachers, different design challenges, and different science content.

One suggestion for future research would be to develop and test engineering design activities coupled with conception-targeted demonstrations or activities, for other science concepts. Research on alternative conceptions points to many areas of science that students have trouble learning. These areas could be explored, and interventions designed to address them.

Middle and high school-aged students are commonly targeted for engineering design interventions (Jeffers, Safferman, & Safferman, 2004). However, research indicates that elementary school students are capable of engineering design as well, and may benefit from the experience in terms of scientific and technological literacy (Brophy, Klein, Portsmore, & Rogers, 2008). Future research will take this approach to using engineering design in science contexts and apply it at the elementary level. Young children are adept at design and constructing; perhaps when targeted toward research-based alternative conceptions in science, engineering design activities will be just as effective at that age level.

This study was conducted in-school during the regular science class. Many engineering outreach programs take place during summer and after-school settings where a less school-like curriculum attracts more students. A final suggestion for future research would be to test this curriculum and others like it with after-school or summer-school groups of students, and determine the best ways to maintain the rigor needed to encourage deep conceptual change in science, while giving students more freedom and opportunities for what they might perceive as “play.” As Duke University engineering professor and author Henry Petroski said:

Children are born engineers. Everything they see, they want to change. They want to remake their world.They want to move dirt and pile sand. They want to build dams and make lakes. They want to launch ships of sticks.... They want to control the universe. They want to make something of themselves (Petroski, 2003, p.206).

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Appendix A
Heat Transfer Evaluation

- This questionnaire is about your understandings of heat transfer.
 - For each question, circle the answer that is closest to your understanding.
 - Be sure to read all the choices before selecting one.
1. You pick up a can of soda off of the countertop. The countertop underneath the can feels colder than the rest of the counter. Which explanation do you think is the best?
 - a. The cold has been transferred from the soda to the counter.
 - b. There is no heat energy left in the counter beneath the can.
 - c. Some heat has been transferred from the counter to the soda.
 - d. The heat beneath the can moves away into other parts of the countertop.

 2. After cooking an egg in boiling water, you cool the egg by putting it into a bowl of cold water. Which of the following explains the egg's cooling process?
 - a. Temperature is transferred from the egg to the water.
 - b. Cold moves from the water into the egg.
 - c. Energy is transferred from the water to the egg.
 - d. Energy is transferred from the egg to the water.

 3. Why do we wear sweaters in cold weather?
 - a. To keep cold out.
 - b. To generate heat.
 - c. To reduce heat loss.
 - d. All of the above.

 4. Amy wraps her dolls in blankets but can't understand why they don't warm up. Why don't they warm up?
 - a. The blankets she uses are probably poor insulators.
 - b. The blankets she uses are probably poor conductors.
 - c. The dolls are made of materials which don't hold heat well.
 - d. None of the above.

 5. As water in a freezer turns into ice,
 - a. the water absorbs energy from the air in the freezer.
 - b. the water absorbs the coldness from the air in the freezer.
 - c. the freezer air absorbs heat from the water.
 - d. the water neither absorbs nor releases energy

 6. On a warm sunny day, you will feel cooler wearing light colored clothes because they
 - a. reflect more radiation.
 - b. prevent sweating.
 - c. are not as heavy as dark clothes.
 - d. let more air in.

7. If you put a metal spoon and a wooden spoon into a pot of boiling water, one will become too hot to touch. Why?
- Metals conduct heat better than wood.
 - Wood conducts heat better than metals.
 - Metals pull in heat because heat is attracted to metals.
 - Wood isn't as strong as metals.
8. On a hot day, the upstairs rooms in a house are usually hotter than the downstairs rooms. Why?
- Cool air is less dense than hot air.
 - Warm air rises and cool air sinks.
 - The upstairs rooms are closer to the sun.
 - Heat rises.
9. You have a can of soda in your lunchbox that you want to keep cold. Which material will work best to keep it cold?
- Aluminum foil wrapped around the soda because metals transfer heat energy easily.
 - A paper towel wrapped around the soda because paper soaks up the moisture.
 - Wax paper wrapped around the soda because wax paper traps the moisture.
 - Your wool sweater wrapped around the soda because wool traps air.
10. When you hold a metal coat hanger in a camp fire to roast a marshmallow, the coat hanger might get too hot to hold. Why might the coat hanger get too hot?
- The heat radiates along the coat hanger.
 - The heat builds up near the flame until it can't hold it anymore and then moves along the coat hanger.
 - Metal atoms vibrate with more energy when they get hot, and they collide with atoms near them, which makes the neighboring atoms vibrate too.
 - Since metals melt in fire, they react very strongly to fire and get hot easily.
11. An aluminum plate and a plastic plate have been in the freezer all night long. When you remove them the next morning,
- The plates have the same temperature.
 - The plastic plate has a higher temperature.
 - The plastic plate has a lower temperature.
 - The aluminum plate has a lower temperature.
12. When placed in direct sunlight, which object will absorb the most radiation?
- a white sweater
 - a snowball
 - some aluminum foil
 - a black sweater

Appendix B Student Entrance Interview Protocol

*Do not use the student's name; use the code during the interview.

*Do not correct students or give them the correct answers if they ask.

*When asking students about their responses on the instrument, encourage them to talk about their thought process they used to answer the problem and how it might differ from pre to post.

My research is focused on how students learn about heat and temperature, and how they feel about science and engineering. I'll be asking you questions about what you know about heat and temperature, and how you feel about science and engineering. Your responses will be kept confidential. Your name will not be used in any final report. If there is a question you do not wish to answer, you can ask to skip it. Participation in this interview is voluntary.

1. What do you already know about heat, temperature, and heat transfer? (*Probe: Ask students if they know what heat is. Ask if they can describe heat. Do they know the difference between heat and temperature? See if they know any of the methods of heat transfer*)
2. [Ahead of time, choose five questions from the pretest.] What was your thinking when you answered this question?
3. Imagine it's winter, and very cold outside and you don't have on gloves or mittens. You have to get on a boat and you have to hold onto something so you won't fall in the water. You can hold onto a shiny metal bar or a brown wooden bar. Which one would you hold onto? Why? (*Probe: Make sure student justifies their reason. If they just say, 'it would be warmer' ask why. Ask why they wouldn't hold on the other choice.*)
4. Now imagine that it's summer time you have to leave your parked car outside in a hot parking lot to go into a store to run an errand. You have a cold can of soda in the car and you don't want it to get warm before you get back to the car. What are some things you can do to keep it from getting warm? (*Probe: give students hints about what materials they may have in the car by showing them these items—a book, a beach towel, a baseball hat, some aluminum foil ... tell them they can be creative. Ask them to justify their answer with scientific reasons.*)
5. Do you like learning science in school? (*Probe: What about it do you like or dislike?*)
6. Have you ever done any invention or design projects in school or at home, like engineering design where you build something? What did you design? Were you part of a team? Did you enjoy doing the design and building? Did you learn any science while doing the design and building project?
7. Do you know anyone who is an engineer? (*Probe: Who, and what have they told you about engineering?*)
8. What do you think engineers do?
9. What do you think engineers are like as people?
10. Would you like to be an engineer? (*Probe: Why? What do you imagine yourself doing?*)

Appendix C Student Exit Interview Protocol

*Do not use the student's name; use the code during the interview.

*Do not correct students or give them the correct answers if they ask.

*When asking students about their responses on the instrument, encourage them to talk about their thought process they used to answer the problem and how it might differ from pre to post.

My research is focused on how students learn about heat, temperature, and heat transfer, and how they feel about science and engineering. I'll be asking you questions about what you have just learned about heat in your science class. Your responses will be kept confidential. Your name will not be used in any final report. If there is a question you do not wish to answer, you can ask to skip it. Participation in this interview is voluntary.

1. What did you learn in this unit on heat, temperature, and heat transfer? (Probe: *Ask students to explain what they learned.*)
2. What were the things (lessons, activities, etc) the teacher did in class that you found to be most helpful in terms of learning about these topics? Probe: *Ask pupils to apply the lessons/activities to the specific concept.*
3. Overall, did you enjoy this unit on heat and temperature and heat transfer? What did you like about the unit? What did you not like about it?
4. [Ask the student the same heat transfer questions that were asked on the pre-interview. Choose additional questions if time allows, particularly ones they got wrong on the pretest and correct on the posttest] What was your thinking when you answered this question? (*If appropriate, ask: Can you tell me why you changed your mind... or didn't change your mind? Was there anything that your teacher did that made you change your mind? Was there anything that you did that made you change your mind? Example- something you read or an experiment you did?*)
5. Imagine it's very cold outside, and you forgot your coat. You're only wearing shorts and a t-shirt. You're at a playground babysitting. You can sit down on a shiny metal bench or a brown wood bench to watch the child. Which one would you sit on? Why? (Probe: *Make sure student justifies their reason. If they just say, 'it would be warmer' ask why. Ask why they wouldn't sit on the other choice.*)
6. Do you like learning science in school? (Probe: *What about it do you like or dislike?*)
7. What do you think engineers do in their careers?
8. What do you think engineers are like as people?
9. Would you like to be an engineer? (Probe: *Why? What do you imagine yourself doing?*)
10. (For students in the experimental group) This is the house you designed for your ice cube penguin. Can you explain why your group decided to build it like this? (Probe: *Ask about individual design components.*) What made you decide to use this particular design? (Probe: *did the demonstrations play any role in your decisions? What learning activities contributed to your decisions?*)