AC 2009-833: ENCOURAGING CONCEPTUAL CHANGE IN SCIENCE THROUGH THE USE OF ENGINEERING DESIGN IN MIDDLE SCHOOL

Christine Schnittka, University of Virginia

Christine Schnittka is a 2009 graduate of the University of Virginia with a Ph.D. in science education. She has ten years experience teaching middle school science, plus masters and bachelors degrees in mechanical engineering.

Randy Bell, University of Virginia

Randy Bell is Associate Professor of Science Education at the University of Virginia.

Larry Richards, University of Virginia

Larry Richards is Professor of Mechanical and Aerospace Engineering at the University of Virginia.

Encouraging Conceptual Change in Science through the Use of Engineering Design in Middle School

Abstract

The United States is suffering from a national crisis in science and math education. At the middle and high school level, US students perform poorly on standardized tests in comparison to other developed countries. Middle school may be the key to capturing students' interest in math and science; this is the time when many children decide they are not interested in science, or not good at math. Additionally, most never get the chance to learn about engineering.

In this study, eighth grade students participated in an engineering design-based curriculum called *Save the Penguins* in order to learn about heat transfer. Students worked in groups of four, and were required to test materials, then design, build, and test a device which would keep a penguin-shaped ice cube from melting in a test oven. The curriculum, designed by the first author, had been pilot tested in five other middle school classes prior to this study. Three groups of students participated in the current study (N=65), equivalent in terms of their seventh grade standardized test scores on reading and math (*p* = .600). All students had the same teacher. Students took a 12-item multiple choice pretest on heat transfer, and the pretest scores were equivalent for all three groups (*p* = .763). Students also took an 11-item Likert scale survey of engineering attitudes, and the pretest scores were equivalent for all three groups (*p*=.111).

Group #1 received the engineering design curriculum, but did not receive five demonstrations aimed at promoting conceptual change. These demonstrations relied on discrepant events, student prediction, and discussion, and targeted well-researched alternative conceptions about heat transfer possessed by young adults. Group #2 did not receive the engineering design curriculum; instead they were taught the same concepts about heat transfer by the same teacher, but in the method she typically taught. Group #3 received the full engineering design curriculum in addition to the five demonstrations designed by the researcher.

Results indicate that all three classes made statistically significant gains in knowledge about heat transfer and that the two classes involved in engineering design activities made statistically significant gains in engineering attitudes. However, when the three classes were compared, Group #3, the class that received the discrepant event demonstrations, made significant and substantial gains in comprehending heat transfer when compared to Group #1, which received the engineering design activities but not the demonstrations (*p* = .02). Qualitative data analysis corroborated these findings.

This research indicates that engineering design activities while beneficial for promoting attitudes towards engineering and making science learning fun and enjoyable for students, are not sufficient by themselves to promote conceptual change in science understanding. A bridge is needed to connect the design activities with the correct scientific conceptions, and in this study, that bridge has been demonstrated to be a series of well-crafted and research-based demonstrations that allow students to make substantial gains in scientific understanding.

Introduction

The purpose of this study is to better understand how middle school students can learn significant science concepts at a deep conceptual level and develop increased interest in and knowledge about engineering through an engineering design challenge that encourages the application of scientific understandings. The research questions guiding the investigation were:

> 1) What are students' conceptions about thermal energy and heat transfer before, during, and after instruction?
> 2) How does learning science through an engineering design challenge change students' attitudes toward and understanding of engineering?
> 3) What are ways in which an engineering design challenge changes students' conceptions of thermal energy and heat transfer?

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.[1,2,3,4]

Overview: *Save the Penguins ETK*

The treatment in this study is a design-based science curriculum called *Save the Penguins*, in which students are challenged to create a dwelling that reduces heat transfer in order to keep a penguin-shaped ice cube from melting. This curriculum was originally developed by engineering students and faculty at the University of Virginia as part of the Virginia Middle School Engineering Education Initiative[5] (VMSEEI), but was subsequently revised and re-written by the first author after pilot testing.

The *Save the Penguins* ETK is designed to address student alternative conceptions about heat, heat transfer, and temperature, address state and national science standards, increase student interest in science, and give students the opportunity to learn more about engineering through the engineering design process. In keeping with the theoretical framework of social constructivism, students work in peer-mediated groups, playing an active role in their learning as they solve problems, and cooperate on the design and testing of the device. The entire ETK takes approximately six 80-minute class blocks to complete.

Many children (and adults) have alternative conceptions about heat, temperature, and heat transfer. The concept of heat as a form of energy evades them.[6] Through cooperative discourse and scaffolding provided by their teacher, this intervention has the potential to help students re-formulate their alternative conceptions of heat, temperature, and heat transfer.

Students also have alternative conceptions about what it means to be an engineer. Some students think engineers only operate trains or repair car engines, and many believe the stereotype of the engineer-as-geek: a socially inept genius male.[7] Many students, females included, fail to see engineering as a helping profession, and therefore cannot understand the beneficial role of engineers in society. This intervention has the potential to help students reformulate their conceptions of what engineering is and what engineers do.

The curriculum for the Save the Penguins ETK is based on science learning objectives derived from state and national standards. These objectives are embedded in the central design challenge. There is a "need to know" each particular science concept built into the curriculum. The performance objectives are derived from the Virginia Standards of Learning[8], the National Science Education Standards[9], and the Benchmarks for Science Literacy[10], and placed in order from the simplest behavior to the most complex on Bloom's taxonomy scale.[11]

The Save the Penguins ETK curriculum is outlined in Figure 1. It begins with the teacher performing some engaging demonstrations about heat transfer. In these demonstrations, the teacher models the experimental methods as the "more knowledgeable other," and students are shown how to undertake these methods on their own in social groups. The teacher then elicits discussions and reflections on the discrepant events students witness as she and the students "talk science." [12] Lemke suggests that talking science involves observing, describing, comparing, analyzing, theorizing and questioning.

As an example of an activity that elicits science discussions, the teacher takes several cans of cold soda out of the refrigerator and wraps them in various materials such as aluminum foil, wax paper, and socks. Students are asked to make predictions about how the temperatures may change in each can. Since students typically think of socks as keeping things warm, and have images of frozen packages of food wrapped in aluminum foil in their freezers at home, they may be quite surprised to see that a wool sock is a better insulator whether the object to be insulated is cold or hot. The teacher describes how experiments are conducted with controls and a variable, and gets students to identify the independent and dependent variables and the controls.

The teacher introduces the concept of heat by first finding out what students think about it. She introduces the concepts of conduction, convection, and radiation, and performs additional demonstrations illustrating all three methods of heat transfer. These demonstrations were designed to provide discrepant events, challenging students' conceptions of heat transfer. Students are then presented with the design challenge: to build a structure which will keep a penguin-shaped ice cube from melting. They are given a budget from which to purchase materials, and instructed to perform experiments to test these different materials before purchasing them, designing, and building the dwelling for their ice penguin. They are provided with digital thermometers, tape and glue, and construction materials such as: bubble wrap, aluminum foil, colored construction paper, colored foam sheets, Mylar film, wooden sticks, cotton balls, and cupcake liners.

Students work in small teams of 3 or 4 students each to test materials, design the dwelling, test the dwelling, and create a story board explicating their progress, design decisions, materials used, and final design.

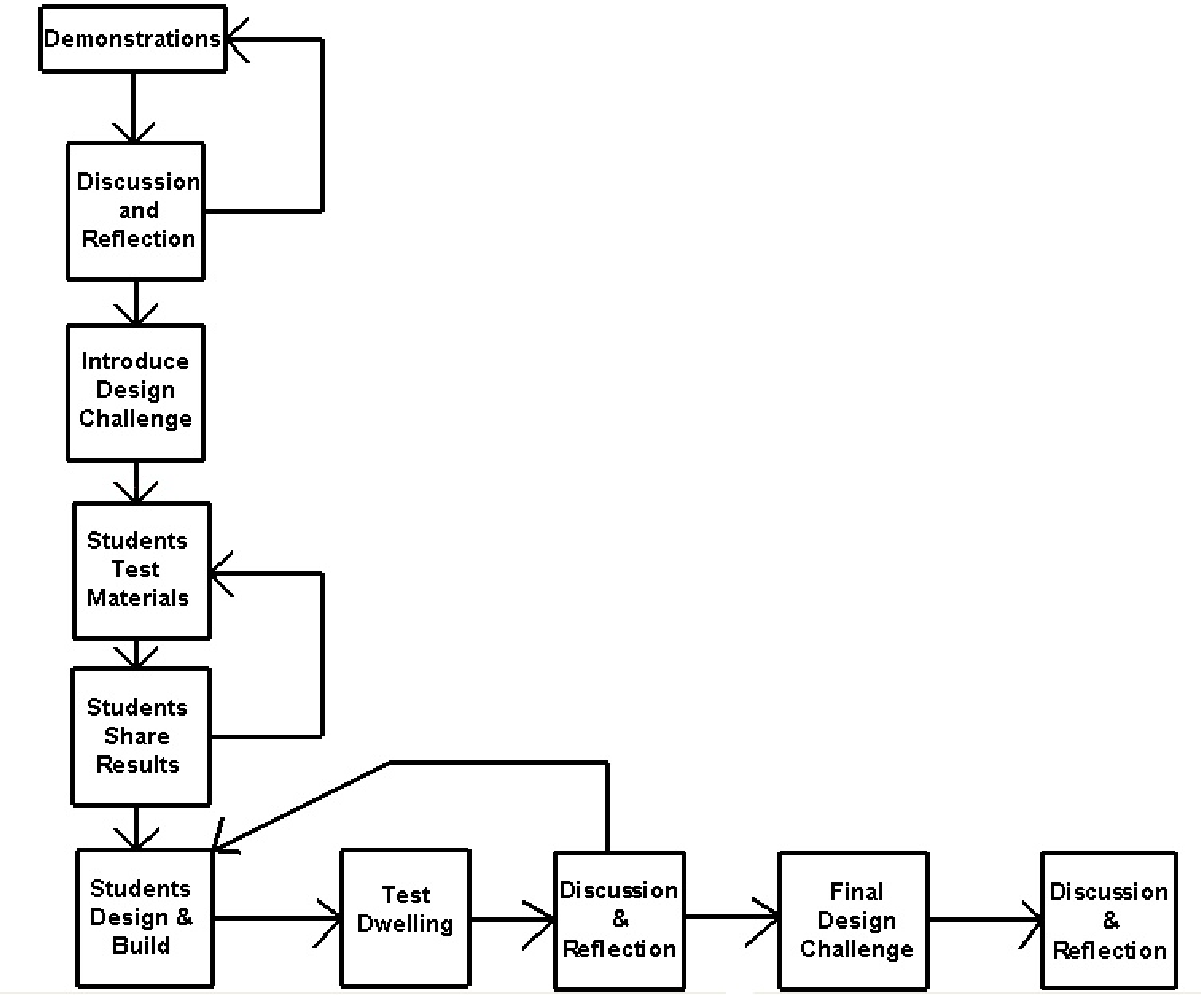

Figure 1. Sequence of events in the Save the Penguins curriculum.

Students perform experiments on different materials or combinations of materials prior to designing their dwelling design. They conduct these controlled experiments at test stations set up around the classroom, and student groups share their results with the rest of the class. Test stations consist of a shielded 150W incandescent lamp pointed downward approximately 45 cm from a black countertop surface. Using their results as a guide, and the results of other student groups, student begin to make decisions about designing a structure that will protect their 10 gram penguin-shaped ice cube in a test oven which has ambient heat, solar radiation, conduction from a black base, radiation from the black base, and convection currents (Figure 2).

Figure 2. Student-designed ice-penguin dwelling.

Students are given a budget and must spend their money on the construction materials they wish to purchase. On the fifth day of the unit, student groups test their first iteration of the design and share their results, their conception of what worked well and what did not, with the class. Each student group starts with a 10 gram ice penguin. Digital scales allow students to accurately measure and record the mass of the remaining ice penguin. The designs are placed into a test oven which consists of a plastic box painted black on the bottom, lined with aluminum foil, with three 150W heat lamps shining down into it. After 20 minutes in the test oven, students are instructed to remove their ice penguin and find the mass of the remaining ice. Students use the ideas and suggestions from their peers to re-design their structure with the goal of improving its performance. They have multiple opportunities to construct, test, and revise their work in keeping with the emphasis on dynamic assessment by social constructivists. Students learn about heat, temperature, controls and variables in experimental methodology, insulators and conductors, and other material properties as they assemble the dwelling for their penguin ice cube.

The final design challenge takes place on the sixth and last day of the unit. After having the opportunity to redesign their dwelling, each student group again starts with a 10 gram ice penguin. After 20 minutes in the test oven, students once again remove their ice penguin and find the mass of their remaining ice. They then finalize the story board poster they have been working so that it describes aspects of the entire activity.

The class as a whole discusses how they think certain materials may have contributed to or hindered heat transfer, how much ice melted during the two challenges, and how modifications to their design may have affected the final outcomes. The class discusses why some designs were more successful than others in preventing heat transfer.

As part of the class discourse, the teacher leads an ongoing discussion about how well-insulated houses protect the health of our environment by reducing the need for fossil-fuels or nuclear fuel to operate power plants. She exposes students to innovations in building construction materials, and describes the role that engineering plays in designing materials that protect our environment and its inhabitants.

The demonstrations

The overall purpose for the special demonstrations was to engage students in cognitive dissonance and encourage conceptual change. Students in the ETK+D class participated in five teacher-led demonstrations about heat transfer. They were designed to provide the scaffolding which would help the student learn scientific concepts, concepts which might be beyond the students' reach when not assisted .[13] In all, these demonstrations consumed one class period out of the five class periods in the unit.

Cans

The purpose of the cans demonstration was to teach students about insulation and help them reform the common conception that aluminum foil is an insulator. The teacher displayed a series of cans that had been in the refrigerator overnight (Figure 3). She wrapped each one in a different material and had students make predictions about which one would be the coldest after an hour. While most students predicted that the can wrapped in aluminum foil would be the coldest, the one wrapped in a wool sock actually was.

The following is an excerpt from the class discussion following the demonstration:

> Teacher: Think about why the wool sock was the best at keeping the can cooler. Why do you typically wear wool socks?
> Students: To keep your feet warm.
> Teacher: Is there such a thing as coldness? Does cold move?
> Students: No.
> Teacher: So, just as the sock keeps the heat from your foot from moving out, the wool sock was keeping the heat...
> Student: From moving in.

Figure 3. The cans demonstration.

This discrepant event led the teacher and her class into a discussion about insulators and conductors, and it helped students understand the concept of insulation. It helped many overcome the common notion that aluminum foil keeps things cold.

Trays

The purpose of the trays demonstration was to teach students about conduction and help them reform the conception that metal is naturally colder than plastic. In the trays demonstration, students were asked to touch both a plastic tray and a silver-plated tray as they were passed around the classroom. Students all concluded with certainty that the silver tray was colder.

The following is an excerpt from the class discussion during the demonstration:

> Teacher: I have two trays over here. I have a silver tray and a plastic tray. Feel them and tell me or predict which tray feels colder.
> Robbie: The metal tray is going to be colder.
> (He touches it.)
> The teacher passes the trays around to all the students so they can touch them.
> Robbie: Eureka! I got it right!
> Teacher: As a general consensus, which did you feel was cooler to the touch?
> Students: Metal.

The class paused at this point, and revisited the trays after the spoons demonstration. There were thermometers secretly taped to the bottom of each tray, and after the spoons demonstration, the teacher revealed the trays' true temperatures.

Spoons

The purpose of the spoons demonstration was to teach students that heat transfers from a warmer mass to a cooler mass. Their conception is typically the opposite when presented with something cold, like an ice cube. When touching an ice cube, they believe that the cold transfers to their hand, for that is what they feel. For the spoons demonstration, students were given a sterling silver spoon and a plastic spoon to hold (Figure 4). An ice cube was placed in each spoon, and students were asked to predict which ice cube would stay frozen the longest. Since they had just felt the silver tray and concluded that it was colder than the plastic one, students all predicted that the silver spoon would keep the ice cube frozen.

Students were astonished, and quickly realized that the ice in the silver spoon was melting rapidly. The teacher gave them space to think about this incongruous event, and guided them into a conception that conduction was occurring from their warmer hands to the cooler ice, not because of any intrinsic temperature difference between the silver and plastic spoons.

Students could see how the heat was affecting the ice cube in the silver spoon much more than in the plastic spoon. They could feel the silver spoon getting cold, and came to the understanding that heat was transferring away from their hands.

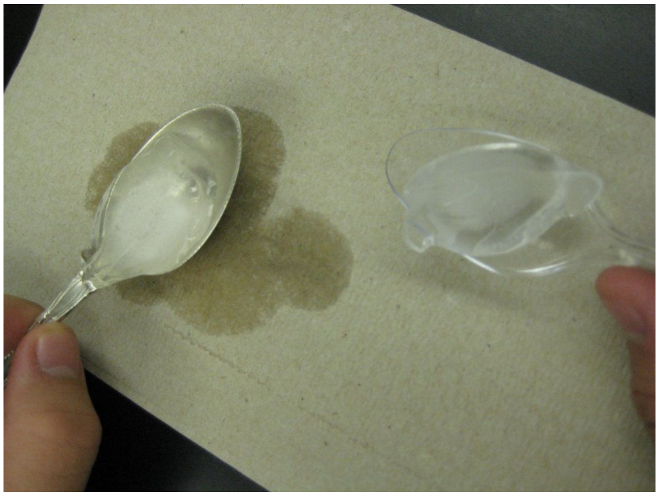

Figure 4. The spoons demonstration.

The following is an excerpt from the class discussion during the demonstration:

> Teacher: Guys, I need you to hold onto the spoons.
> Amy: It's melting already!
> Wally: That's because she dropped it.
> Amy: No, it's because metal is a conductor.
> Diana: This hand is freezing because of conduction.
> Stacey: Oh yeah, the metal one will melt faster because the heat is going into the spoon.
> Dara: *Isn't that cool? I never would have thought that. Metal is a conductor and heat goes from a warm area to a colder area and since our hands are warm with our body heat, it goes into the ice.*
> Beck: The heat from the spoon is going into the ice cube.
> Teacher: How is the heat getting to the spoon?
> Beck: From your hand

After the spoons demonstration, the teacher turned the silver and plastic trays over and revealed aquarium thermometers taped to the bottom. The trays were actually the same temperature. Students were shocked and amazed that their senses could fool them. Dara said out loud, “That's just freaky. It's scary!” This demonstration led many students to a sophisticated understanding that the perception of “cold” is actually the science of heat transferring from their bodies to another place.

The House

The purpose of the house demonstration was to teach students about convection. While students may have heard of convection in terms of liquid flow in a pot of water on the stove, many were not familiar with the concept that all fluids can experience convection, even gases. The teacher presented a cardboard house with a black painted roof (Figure 5). A heat lamp was shining on the roof and thermometers measured the temperature of the air in the attic and on the first “floor.” Mylar was not draped over the roof so the temperature in the “attic” quickly got very hot.

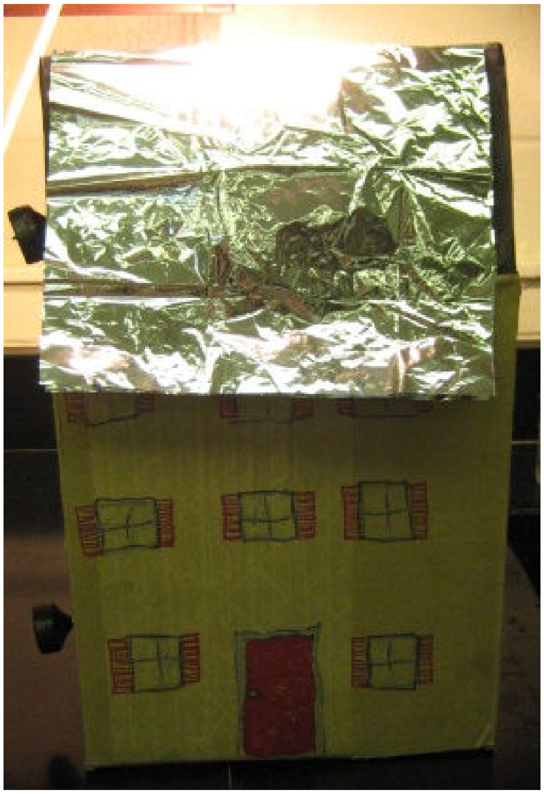

Figure 5. The house demonstration with Mylar draped over the roof

Students were asked to record these two temperatures. After a few minutes under the lamp, the difference was greater than 30 degrees Fahrenheit. Then the teacher took the house out from under the lamp and flipped it upside down. She asked students to predict the temperature changes, and asked them to explain what was going on.

Teacher: What do you think is happening?
Timmy: Hot air is rising.
Ed: The cool air that was on the bottom is sinking.
Teacher: We see this one is falling and this one is rising what we call that?
Diana: Convection currents.

Students also discussed why the attic of the house was so much hotter than the first floor. Some students postulated that it was because the roof was closer to the heat lamp. Others noticed that the roof was painted black and anticipated that the black roof was absorbing the light somehow.

Teacher: Let's talk about this what type of heat transfer is happening here.
Diana: Radiation.
Ed: The black roof is attracting and trapping it.
Teacher: Why is the attic getting hot?
Amy: Heat rises.
Teacher: Does heat rise?
Ed: Hot air rises.
Teacher: Heat can go any which way it as long as it goes to a cooler place.

The teacher did not correct the student's statement that the black roof was "attracting" the radiation. Nor did she address the issue that many factors were causing the attic to become so hot: proximity to the lamp, the color of the roof, and the fact the hot air was trapped with no place to escape. However, it did give students an internal visual image of hot air rising and cooler air sinking in the house.

Mylar

The purpose of the Mylar demonstration was to teach students about radiation and the way radiation can be reflected by shiny surfaces. The piece of Mylar could have been used in a house demonstration to illustrate how radiation is reflected, but instead the teacher had a student come up to the heat lamp and place his hand underneath the lamp. He quickly complained that it was hot. The teacher slipped the thin film of shiny Mylar between his hand and the lamp, and immediately he said that his hand was not hot anymore. The following is an excerpt from the class discussion during the demonstration:

> Teacher: I'm going to put this Mylar space blanket over his hand.
> Beck puts his hand back under the light and the teacher alternately places and removes the Mylar.
> Beck: It's cool
> Beck: It's hot
> Beck: It's cold
> Teacher: You all get a sample of this. Why do you think it worked that way?
> Ed: It prevents the radiation from going through.
> Robbie: Since the heat causes radiation, it reflects off the aluminum foil (Mylar).

The Mylar demonstration took 5 minutes to complete. Students passed around the piece of Mylar and realized that it was translucent. They could see right through it, but it was shiny enough to reflect most of the light and prevent Beck's hand from burning. This demonstration proved to be very useful to students as they designed their penguin-shaped ice cubes. Most student teams covered their dwellings in Mylar.

Participants

Participants in this study consisted of a teacher and her 71 advanced-level eighth-grade students. The first 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 consisted of 27 students: 17 male and 10 female. All students were Caucasian. The third 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, Ms Smith, had 4 years of full-time middle school science teaching experience. She was working part-time on a M.Ed. 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. She only had 1 year of experience teaching eighth grade physical science prior to this study.

Site

Montebello Middle School is 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 year 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.

Design of Study

The design of this study was mixed methods and used the quasi-experimental, single treatment control group design, meaning that the treatment was manipulated, but that the experiment lacked random assignment.[14] Miss Smith taught three advanced-level eighth grade science classes. The first class was eventually designated the ETK class, the second the Control class, and the third the ETK+D class. The first class was chosen to be the experimental group receiving the ETK treatment without the five special demonstrations. The second class was to be chosen to be the control group. In order to determine the effects of five special demonstrations designed to target alternative conceptions about heat transfer, the third class received the ETK treatment with demonstrations. This class was called the ETK+D class.

In order to fairly choose which group would be the control group, which group would receive the ETK+D treatment, and which group would receive the ETK treatment without the demonstrations, Miss Smith provided the researcher with an anonymous list of her advanced-level students' 7th grade standardized test results in reading and math for each class. The math and reading scores were added, and that value was compared between classes with statistical procedures. The three classes were demonstrated to be statistically equivalent in terms of academic achievement in seventh grade math and language arts. However, the Control class differed in that many more students in that class had taken Algebra in seventh grade when compared to the other two classes. While 33% of students in the ETK class took algebra in seventh grade and 35% of students in the ETK+D class took algebra in seventh grade, 56% of students in the Control class took algebra in seventh grade. Therefore, the Control class was purposefully chosen because students in that class might possess an academic advantage due to their more advanced mathematics abilities. In that way, it could be determined if design-based science activities could help students with lower mathematics abilities make progress in science concept understandings as well as their higher-ability peers.

A coin toss was used to determine which of the remaining two classes would receive the ETK treatment and which would receive the ETK+D treatment.

Three treatments

In order to test the effects of engineering design activities and scaffolding demonstrations targeted to alternative conceptions about heat transfer, three treatments were used for this study. The ETK class was taught heat transfer through the engineering design-based ETK, *Save the Penguins*. The Control class was taught heat transfer through the teacher's typical instruction, the textbook-based curriculum the teacher used in the previous year. The ETK+D class was taught through the engineering design-based ETK, *Save the Penguins*, and they were shown the five demonstrations developed for this study. These demonstrations took approximately one class period. The other two classes watched an educational PBS video that contained other visual imagery and demonstrations, and the teacher showed them demonstrations she had used the year before in her typical instruction.

The three different interventions each lasted six 80-minute classroom periods and the researcher videotaped all instruction, took detailed observation notes, and interviewed approximately half the students from each class prior to and after the interventions. All interviews were audio recorded and transcribed for analysis. Qualitative analysis involved analytic induction, the process of open coding, collapsing codes, and developing themes and assertions, then testing assertions against the data corpus. Quantitative analysis involved statistically analyzing the pre and posttests for both the heat transfer and engineering attitudes tests.

Instruments

The two instruments administered both as pre- and posttests were:

1. Heat Transfer Evaluation (HTE); The purpose for administering the HTE was to assess what alternative conceptions students had about heat transfer prior to the intervention, and then assess the degree to which learning about heat transfer took place as a result of the intervention. The content-based Heat Transfer Evaluation is a 12-question multiple choice dichotomous (right or wrong) test. Field testing with students prior to the dissertation research has helped establish expected high and low scores on this test. Each student earned a score on the test as a whole.

2. Attitudes Toward Engineering Survey (ATES): The purpose for administering the ATES was to evaluate whether the intervention influenced how students perceived what engineers do, what engineers are like, and the value of engineering as a profession. The Attitudes towards Engineering Survey contains 11 Likert-scale items with five choices: strongly disagree, disagree, neither agree nor disagree, agree, and strongly agree. Field testing of this attitudes survey with students prior to the dissertation research established a range of expected results for the surveys.

Both instruments and the details of their development and validation are presented in the first author's PhD dissertation.[15]

Results

Heat Transfer Evaluation Posttests

All students who took the HTE pretest two weeks prior to instruction took the HTE as a posttest immediately after the intervention was complete. Paired *t*-tests were used to assess whether change occurred in all three classes in terms of students' answers on the Heat Transfer Evaluation. In all cases, $p < .001$. The ETK class, $n = 21$, obtained a posttest mean score of 6.43 (*SD*=2.52) with a change of 2.1 out of 12 points. The Control class, $n = 27$ students, obtained a posttest mean score of 7.19 (*SD*=1.84) with a change of 2.56 out of 12 points. However, the ETK+D class, $n = 23$ students, obtained a posttest mean score of 8.22 (*SD*=1.94) with a change of 4.22 out of 12 points.

An ANOVA demonstrated that these classes were statistically not equivalent in terms of their change in heat transfer knowledge across time $F(2,68) = 6.659$, $p= .002$, with an effect size of $r = .29$. Post hoc Tukey's test revealed that there was a significant difference between the ETK class and the ETK+D class with $p = .003$ and a significant difference between the Control class and the ETK+D class with $p = .016$ while the difference between the ETK class and the Control class was not significant with $p = .724$. Figure 6 illustrates the interaction between student achievement and time on the HTE. Students in the ETK+D class had the lowest test scores on the HTE pretest and the highest scores on the HTE posttest.

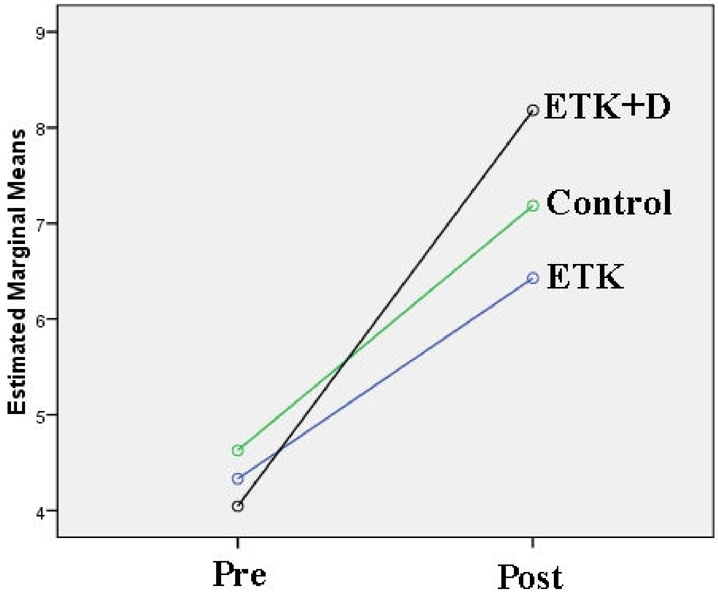

Figure 6. The interaction between classes on the HTE pre- and posttest

These results, along with results from exit interviews with students in each class, support the assertion that students in the ETK+D class learned the science concepts to a greater degree and deeper conceptual level than students in the other two classes. Thus, students with engineering design experience and demonstrations targeting alternative conceptions had more sophisticated conceptions of heat transfer than students with engineering design experience alone or typical instruction.

Summary of heat transfer conceptions after the intervention

Based upon HTE posttests and exit interviews, it can be concluded that students in the ETK+D class, the class that received the ETK and the scaffolding demonstrations made more gains in most areas of the science of heat 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 claimed that “heat rises” and that “cold transfers.” Students with the engineering design treatment coupled with demonstrations that targeted research-based alternative conceptions understood insulators and conductors better. They were able to apply their knowledge to new situations. Whereas students in the ETK+D class were the lowest performing class on the heat transfer pretest and entrance interviews, they were the highest performing after the unit concluded. They made the most incorrect statements about heat transfer during the entrance interviews and the fewest incorrect statements about heat transfer during their exit interviews. As evidenced by statements made in their exit interviews, their direct experiences applying their knowledge to a 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 teacher-led demonstrations, allowed them to make better sense of the science and apply it more fully toward the engineering design task. Ten of the 12 designs 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.

Engineering Attitudes and Understanding

How does learning science through an engineering design challenge impact students’ attitudes toward and understanding of engineering?

Prior to the intervention, students from all three classes were administered the Attitudes toward Engineering Survey (ATES). Scores for questions with negative statements about engineering were reversed so that a negative score of 5 would equal a positive score of 1. Scores from students in the three classes were compared to ascertain whether or not they were statistically similar in terms of attitudes toward engineering. The three classes of students scored statistically the same on their engineering attitudes pretests, so they were considered to be equivalent groups. Thus, students’ attitudes toward and understanding of engineering were similar across all three groups prior to instruction.

The ETK class, with n = 21 students, obtained a mean pretest score of 3.35 out of 5 points on the Likert scale ATES. The Control class, with n = 27 students, obtained a mean pretest score of 3.52 out of 5 points on the ATES. The ETK+D class, with n = 23 students, obtained a mean pretest score of 3.64 out of 5 points on the ATES. These scores were slightly better than the Likert scale value 3, which indicates a neutral attitude. It was expected that students would score around the neutral middle of the scale. Scores were normally distributed for each class with homogeneous variances. The measure of reliability (Cronbach's alpha) for this instrument with these groups of students was .758 for the ETK class, .778 for the Control class, and .768 for the ETK+D class. An ANOVA demonstrated that these classes were statistically equivalent in terms of engineering attitudes with F (2, 68) = 2.271, p = .111, with an effect size r = .18.

The students in all three classes generally recognized engineering as a profession where people design things that are practical and useful, however the entrance interviews revealed that some students had very different ideas about what engineers actually design. Generally, all classes perceived engineering to be important to the United States' economic success and useful in everyday life. Overall, the differences as a whole were not significant between classes.

Students were asked about their perceptions of engineering as a career and of engineers as people in their entrance interviews. Students categorized the tasks performed by engineers into nine main categories: engineers build things, design things, fix things, make things, think about things, use things, operate things, work on things, and know things.

The results from the entrance interviews were similar across the three classes prior to instruction. Most students did not personally know an engineer, and if they did, they did not have a clear idea of what an engineer might do for a job. Students commonly conflated engineering with fixing cars, driving trains, and building and fixing things. However, the most common personality traits assigned to engineers were positive ones; that they are hard working, they like math and science, they are patient, and they are smart.

Attitude toward Engineering Survey – changes over time

The ETK class, *n* = 21, obtained a pretest score of 3.35 (*SD*=.45) and a posttest score of 3.57 (SD=.38) out of 5 points on the ATES. A paired samples t-test revealed that this difference is significant (significance defined as at less than .05/3 = .0167) at *t* (20) = 3.739, *p* = .001 with an effect size *r* = .26. The Control class, *n* = 27, obtained a pretest score of 3.52 (*SD*=.45) and a posttest score of 3.61(*SD*=.49) out of 5 points. A paired samples t-test revealed that this difference is not significant at *t* (26) =1.347, *p* = .190 with an effect size *r* = .10. The ETK+D class, n = 23, obtained a pretest score of 3.64 (*SD*=.45) and a posttest score of 3.90 (*SD*=.53) out of 5 points. A paired samples *t*-test revealed that this difference is significant at *t* (22) = 2.657, *p* = .014 with an effect size *r* = .26. Figure 7 shows change over time for all three classes on the engineering attitudes assessment. It is obvious that whereas the slope for the Control class is small, the slopes for the engineering design classes are nearly parallel and steeper. While students in the ETK+D class started out with a higher attitude toward engineering, their attitude increased more than the other two classes, but only slightly more than students in the ETK class. When these scores were compared with each other using a repeated-measures ANOVA, the overall difference was not significant between classes.

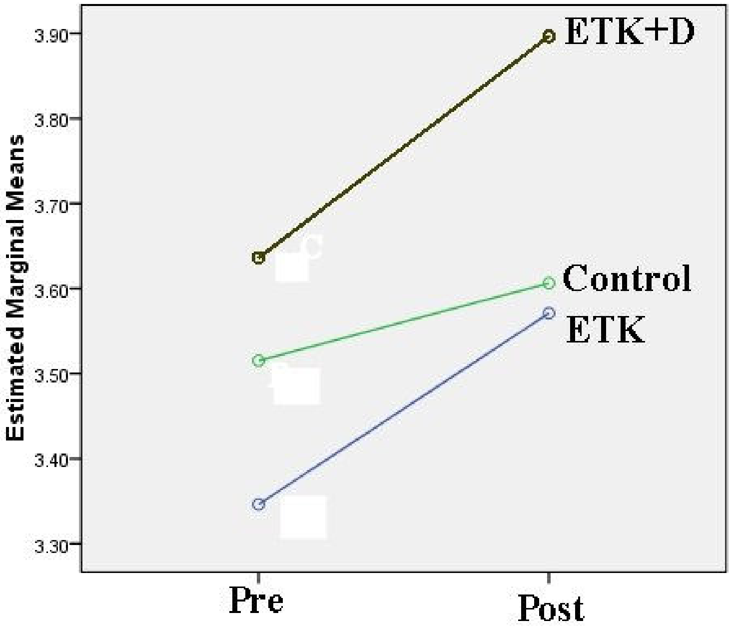

Figure 7. Estimated marginal means for all three classes: Pretest and posttest scores on ATES

Figure 8 also illustrates how students in each class performed on the Attitudes toward Engineering Survey both pre- and posttest.

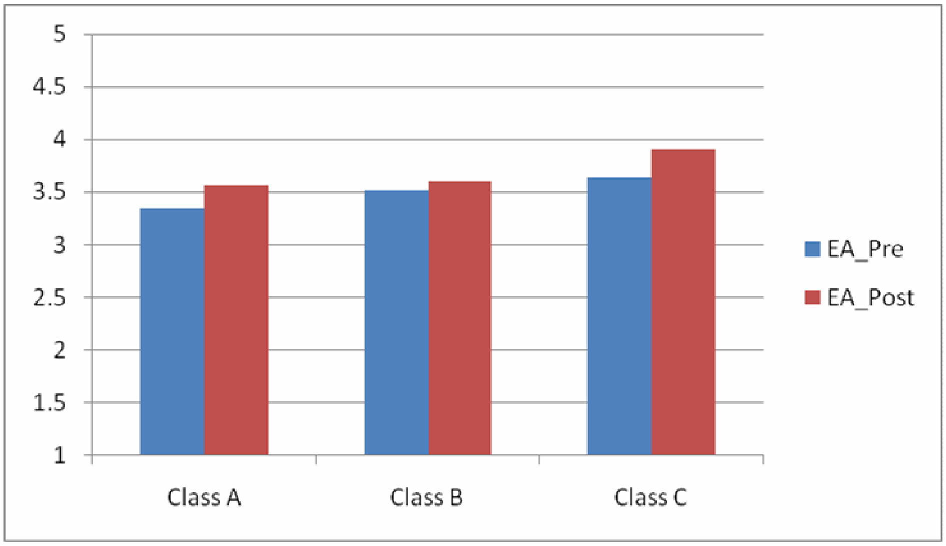

Figure 8. Pre- and posttest scores on Attitude toward Engineering Survey.

The very small difference in attitudes toward engineering could have occurred in the Control class for a number of factors. Students in other classes could have told them about their class activities. Students could have picked up some engineering from a final project called Excellent Energy, where students studied insulation used for homes and bodies. Time or maturation could have played a factor as students might have been exposed to engineering concepts at home or on television and in the news. Regardless, this change was not significant whereas changes in the engineering design classes were significant.

Gender differences

While overall, students in the engineering design classes had a positive change toward engineering, when this trend was examined by gender; it became apparent that only the females' scores engendered this positive change. Thus, female students' attitudes toward engineering changed during the design intervention but male students' attitudes did not.

Male students in the ETK class, *n* = 9, obtained a pretest score of 3.58 (*SD*=.50) and a posttest score of 3.75 (*SD*=.50) out of 5 points on the ATES. A paired samples *t*-test revealed that this difference is not significant (significance defined as less than .05/3 = .0167) at *t* (8) = 2.290, *p* = .051 with an effect size *r* = .17. Male students in the Control class, *n* = 17, obtained a pretest score of 3.56 (*SD*=.40) and a posttest score of 3.59 (*SD*=.50) out of 5 points. A paired samples *t*-test revealed that this difference is not significant at *t* (16) = 0.296, *p* = .771 with an effect size *r* = .03. Male students in the ETK+D class, *n* = 12, obtained a pretest score of 3.79 (*SD*=.45) and a posttest score of 3.96 (*SD*=.60) out of 5 points. A paired samples *t*-test revealed that this difference is not significant at *t* (11) = 1.147, *p* = .276 with an effect size *r* = .16.

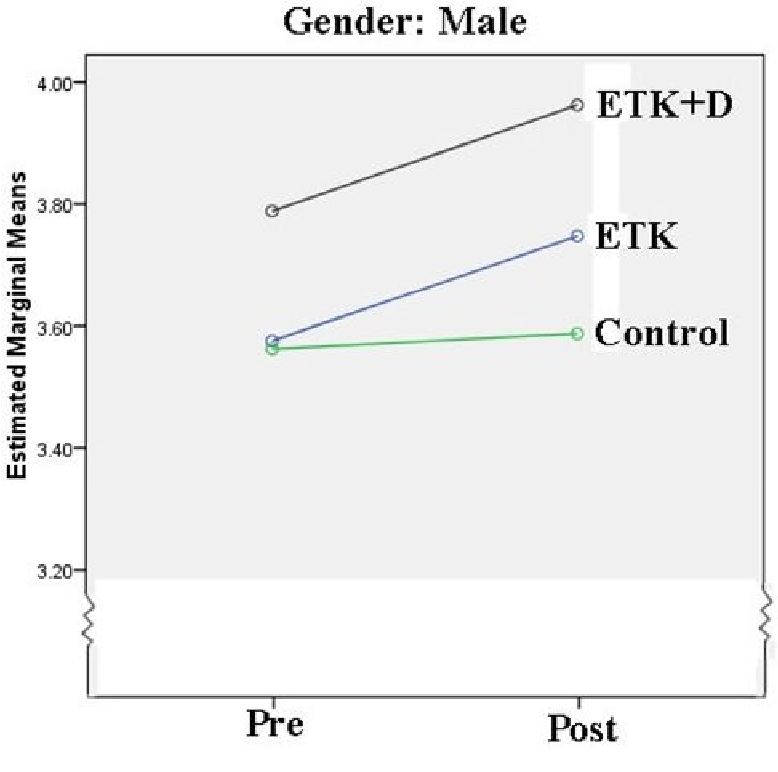

Figure 9. Male students' attitudes toward engineering

Female students in the ETK class, *n* = 12, obtained a pretest score of 3.17 (*SD*=.34) and a posttest score of 3.44 (*SD*=.20) out of 5 points. A paired samples *t*-test revealed that this difference is significant (significance defined as less than .05/3 = .0167) at *t* (11) = 2.939, *p* = .013 with an effect size *r* = .44. Female students in the Control class, *n* = 10, obtained a pretest score of 3.44 (SD=.53) and a posttest score of 3.64 (*SD*=.49) out of 5 points. A paired samples *t*-test revealed that this difference is not significant at *t* (9) = 1.904, *p* = .089 with an effect size *r* = .19. Female students in the ETK+D class, *n* = 11, obtained a pretest score of 3.47 (*SD*=.60) and a posttest score of 3.83 (*SD*=.46) out of 5 points. A paired samples *t*-test revealed that this difference is significant at *t* (10) = 2.905, *p* = .016 with an effect size *r* = .32.

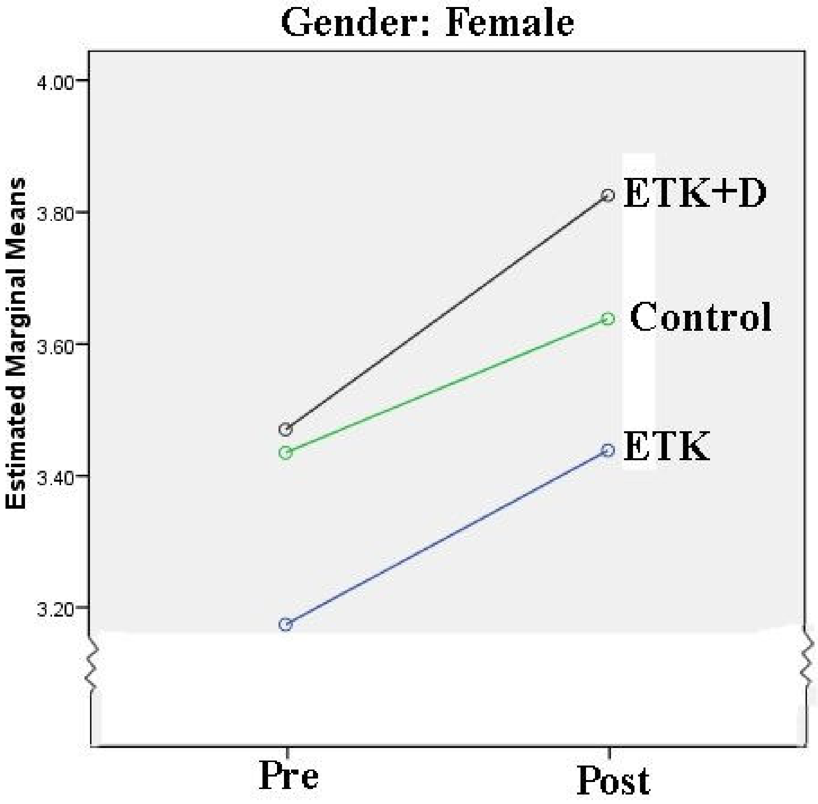

Figure 10. Female students' attitudes toward engineering

There was a significant difference in engineering attitudes from pre- to posttest for both engineering design classes, but not for the Control class. That was to be expected. However, when data were broken down by gender, something interesting emerged. The female students in the engineering design classes enabled that difference. This can be interpreted to mean that for the males, the design activity did not change their attitudes toward engineering, but for the females it did. In all classes, male students started off with a higher score on the ATES pretest. Male students also ended up with a higher score on the ATES posttest in the ETK class and the ETK+D class, but the change over time was less than that of female students. The combination of the design challenge and the scaffolding demonstrations was especially effective in promoting female students' attitudes toward engineering.

Overall findings

Findings indicated that students overwhelmingly possessed misconceptions about both heat transfer and engineering prior to the interventions. The three classes were statistically equivalent on the HTE in terms of concept knowledge about heat and energy, insulation, and all facets of heat transfer prior to the interventions. Students in all the classes also had similar ideas about engineering and what engineers do, and had statistically equivalent scores on the ATES pretest. While all three classes made statistically significant gains in their knowledge about heat transfer, students in the ETK+D class- the class that had the lowest pretest score on the Heat Transfer Evaluation - made the highest and most significant gains over the other two other classes. Qualitative data analysis confirms this assertion as well. Therefore, it is not enough to merely provide students with engineering design activities and expect conceptual change to occur. Scaffolding, in the form of specifically designed demonstrations- which were developed to provoke cognitive dissonance and encourage conceptual change- has been shown to be efficacious in helping students learn the science of heat transfer through the engineering design activity.

Engineering attitudes changed significantly in the two classes that received the engineering design intervention, and did not change to a significant degree in the control class. Thus, the engineering design intervention had a positive effect on student attitudes toward engineering. Qualitative data analysis confirms this assertion as well, and describes changes in students' knowledge about engineering in these two classes.

Gender differences were evident: Engineering design activities promoted greater gains in positive attitudes toward engineering for the female students than for the male students.

Implications from this study can inform teachers' use of engineering design activities in science classrooms for the purpose of teaching about engineering and also teaching science content at a deep conceptual level. Results may also be of interest to science curriculum developers and engineering educators involved in developing engineering outreach curricula for middle school students. With many states promoting STEM initiatives to encourage the rigorous teaching of science, technology, engineering and mathematics, the results of this study may help strengthen the results of those efforts.

References

1. Ferguson, R.L. (2007). Constructivism and social constructivism. In G.M. Bondner & M. Orgill (Eds.), *Theoretical frameworks for research in chemistry/science education* (pp. 28-49). Upper Saddle River, NJ: Pearson Education, Inc.

2. Driver, R., Guesne, E., & Tiberghien, A., (Eds.) (1985). *Children's ideas in science.* Philadelphia: Open University Press.

3. Driver, R., Squires, A., Rushworth, P., & Wood-Robinson, V. (1994). *Making sense of secondary science: Research into children's ideas.* London: Routledge.

4. Puntambekar, S., & Kolodner, J.L. (2005). Toward implementing distributed scaffolding: Helping students learn science from design. *Journal of Research in Science Teaching, 42*, 185-217.

5. Richards, L.G., Hallock, A.K., & Schnittka, C.G. (2007). Getting them early: teaching engineering design in middle schools. International Journal of Engineering Education, 23, 874-883.

6. Erickson, G. L., & Tiberghien, A. (1985). Heat and temperature. In R. Driver, E. Guesne, & A. Tiberghien (Eds.), *Children's ideas in science* (pp. 52–84). Philadelphia: Open University Press.

7. Knight, M., & Cunningham, C. (2004). Draw an Engineer Test (DAET): Development of a tool to investigate students' ideas about engineers and engineering. *Proceedings of the 2004 Annual Meeting of the American Society for Engineering Education*. Retrieved March 8, 2008, from http://asee.org/acPapers/2004-1188_Final.pdf

8. Virginia Department of Education. (2003). *Science standards of learning for Virginia public schools*. Richmond, VA: Commonwealth of Virginia. Retrieved March 8, 2008 from http://www.doe.virginia.gov/go/Sols/sciencesol.pdf

9. National Research Council. (1996). *National science education standards*. Washington, DC: National Academies Press.

10. American Association for the Advancement of Science. (1993). *Benchmarks for science literacy*. New York: Oxford University Press.

11. Bloom B. S. (1956). *Taxonomy of educational objectives, handbook 1: The cognitive domain*. New York: David McKay.

12. Lemke, J.L. (1990). *Talking science: Language, learning, and values*. Norwood, NJ: Ablex Publishing Corporation.

13. Wood, D., Bruner, J., & Ross, G. (1976). The role of tutoring in problem solving. *Journal of child psychology and psychiatry and allied disciplines, 17*, 89-100.

14. Shadish, W.R., Cook, T.D., & Campbell, D.T. (2002). *Experimental and quasi-experimental designs for generalized causal inference*. Boston, MA: Houghton Mifflin Company.

15. Schnittka, C.G. (2009) *Engineering Design Activities and Conceptual Change in Middle School Science* PhD Dissertation, Curry School of Education, University of Virginia, Charlottesville VA .