ENGINEERING DESIGN ACTIVITIES
AND
CONCEPTUAL CHANGE IN MIDDLE SCHOOL SCIENCE

A Dissertation

Presented to

The Faculty of the Curry School of Education

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by

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Abstract

The purpose of this research was to investigate the impact of engineering design classroom activities on conceptual change in science, and on attitudes toward and knowledge about engineering. Students were given a situated learning context and a rationale for learning science in an active, inquiry-based method, and worked in small collaborative groups.

One eighth-grade physical science teacher and her students participated in a unit on heat transfer and thermal energy. One class served as the control while two others received variations of an engineering design treatment. Data were gathered from teacher and student entrance and exit interviews, audio recordings of student dialog during group work, video recordings and observations of all classes, pre- and posttests on science content and engineering attitudes, and artifacts and all assignments completed by students.

Qualitative and quantitative data were collected concurrently, but analysis took place in two phases. Qualitative data were analyzed in an ongoing manner so that the researcher could explore emerging theories and trends as the study progressed. These results were compared to and combined with the results of the quantitative data analysis. Analysis of the data was carried out in the interpretive framework of analytic induction.

Findings indicated that students overwhelmingly possessed alternative conceptions about heat transfer, thermal energy, and engineering prior to the interventions. While all three classes made statistically significant gains in their
knowledge about heat and energy, students in the engineering design class with the targeted demonstrations made the most significant gains over the other two other classes. Engineering attitudes changed significantly in the two classes that received the engineering design intervention.

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 conceptual change.

3) A middle school teacher can successfully implement an engineering design-based curriculum in a science class.

Results may also be of interest to science curriculum developers and engineering educators involved in developing engineering outreach curricula for middle school students.
Department of Curriculum and Instruction  
Curry School of Education  
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Charlottesville, Virginia  

APPROVAL OF THE DISSERTATION

This dissertation, Engineering Design Activities and Conceptual Change in Middle School Science, has been approved by the Graduate Faculty of the Curry School of Education in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Randy L. Bell  
Joe Garofalo  
Walter F. Heinecke  
Susan L. Mintz  
Larry G. Richards  

March 16, 2009  
Date
DEDICATION

To my husband, Dan Schnittka, whose constant love and support over the past 25 years made this endeavor possible from start to finish. Three degrees and three children later, I would be only half a person without his having journeyed through life with me.

To my beloved children: Jessica, Andrea, and Daniel, who have always been my very best teachers of all.
I would like to thank my advisor Randy Bell for his steadfast support, tutelage, mentoring, and encouragement over the past 5 years. While it is painful to grow wings and fly, I hope that Randy always knows how grateful I am to him for helping me exercise and use these wings. He is a falconer at heart, and uses that gift with his students as well. I hope to do him proud and fly well.

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Thanks go out to my mother the teacher- Ursula Higgins, who always knew in her heart that this was to be my career path, and set me on the course at an early age with much bribery and cajoling, and although I think I got here on my own, I know I did not- for which I am now extremely grateful.

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CHAPTER 1: THE PROBLEM

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). However, a more important goal of science education is to increase scientific and technological literacy for all, not just for future scientists and engineers. Scientific knowledge is no longer a luxury for American students. An understanding of both science and its applications in technology are needed by all of society. “Progress in science and technology has reached the place where their future is dependent upon an education that is appropriate for meeting the challenges of an emerging scientific revolution” (Hurd, 1958, p.14). Hurd’s statement is as true today as it was 50 years ago. Science education is in a state of transition due to the rapid movement of our society into a new technological era. A supply of quality scientists, mathematicians, and engineers is needed, but also a population in which every educated person is literate in science and technology.

According to the Benchmarks for Science Literacy, a scientifically literate person is one who is able to “use the habits of mind and knowledge of science, mathematics, and technology they have acquired to think about and make sense of many of the ideas, claims, and events they encounter in everyday life” (American Association for the
Scientific literacy enables a person to better observe, reflect upon, and comprehend the world around them, and thus become better decision-makers. The National Science Education Standards [NSES] (National Research Council [NRC], 1996) define scientific literacy as “knowledge and understanding of scientific concepts and processes required for personal decision making, participation in civic and cultural affairs, and economic productivity” (p. 22). It enables a person to ask and find answers to their questions, describe and predict natural phenomena, and comprehend and discuss scientific news. Scientific literacy also implies that a person can “identify scientific issues underlying national and local decisions and express positions that are scientifically and technologically informed” (p. 22). These two documents, the NSES and Benchmarks for Science Literacy, inform our current view of what it means to be a scientifically literate person in today’s society. Both documents subsume the concept of technological literacy, a goal closely related to and interwoven with scientific literacy. As stated in the NSES, “The relationship between science and technology is so close that any presentation of science without developing an understanding of technology would portray an inaccurate picture of science” (p. 190).

Despite the emphasis on scientific literacy by the two national science education standards, only 17% of US adults were considered to be scientifically literate at the end of the 20th century (Miller, 2004). In 2006, the Organisation for Economic Co-operation and Development (OECD) administered the Programme for International Student Assessment (PISA) assessment of science literacy to over 400,000 students age 15, in 57 countries. The test assessed students’ abilities to identify scientific issues, explain
scientific phenomena, use scientific evidence, demonstrate knowledge of scientific concepts, and demonstrate knowledge about how scientific inquiry operates. The United States’ 15-year-old students ranked 29th place with a score a 489, statistically below the mean of 500 (OECD, 2007).

As an analogy to scientific literacy- which comprises a body of scientific knowledge, a set of scientific methods/processes, and a way of knowing about science (Bell, 2007), technological literacy comprises a body of technical knowledge, a set of technical methods and processes, and knowledge about the nature of technology (Pearson & Young, 2002). The International Technology Education Association (ITEA) defines technological literacy in its document, Technology for All Americans as the ability to “understand the nature of technology, appropriately use technological devices and processes, and participate in society’s decisions on technological issues” (ITEA, 1996, p.1), stating that the ways in which people develop and use technology have a great impact upon future generations and the Earth’s ability to continue to sustain life.

Despite the fact that an emphasis on scientific and technological literacy is present in three major educational reform documents: the Benchmarks for Science Literacy (AAAS, 1993), the National Science Education Standards (NRC, 1996), and the International Technology Education Association’s Standards for Technological Literacy (ITEA, 2000), there is virtually no emphasis placed on technological literacy in today’s K-12 curricula in the United States. The closest that most K-12 schools come to actually promoting technological literacy is through elective technology education courses that have low status in both K-12 schools and universities, focusing primarily on vocational
studies (Bugliarello, 2000; Gray, Wang, & Malizia, 1995; Pearson & Young, 2002). Pennsylvania, Massachusetts, Delaware, New Jersey, New Hampshire, New York, and Vermont have well integrated technological topics into the science standards required for all students, but over a third of the states have very little, if any, technology standards integrated into their science standards (Chaker, 2008; Koehler, Farclas, Giblin, Moss, & Kazerounian, 2007; Massachusetts Department of Education, 2006). The measure of technological literacy held by American citizens is currently an unknown.

No good measures of technological literacy are being used in the United States today. A small number of organizations and individuals—including some outside this country—have developed a variety of tests and surveys to try to get a handle on what people know or believe about technology, but most of these efforts have either been short lived or have failed to provide the kind of data necessary for drawing useful conclusions about technological literacy (Garmire & Pearson, 2006, p. 20).

**Technology education and educational technology**

There is some confusion in the education community about the use of the terms technology and technological literacy.

Technology is described as the way people modify the natural world through design to meet their needs and desires (ITEA, 2000; Pearson & Young, 2002; NRC, 1996). It is not, as most people seem to think, applied science (Bybee, 2000; Hayden, 1989; ITEA, 1996; Pearson & Young, 2002; NRC, 1996), nor is it solely about computers and their applications (Rose, Gallup, Dugger, & Starkweather, 2004). The American Association for the Advancement of Science (AAAS, 1993) describes technology as that which “extends our abilities to change the world: to cut, shape, or put together materials;
to move things from one place to another; to reach farther with our hands, voices, and senses" (p. 41) and states that technology is used to change the world to help us survive or thrive. Based on an extensive review of literature, Hayden (1989) defined technology as “a set of processes by which resources are utilized to extend human potential within a given environmental context” (p. 229).

Many people, even educators, confuse technology education with educational technology. While the goal of technology education is technological literacy, and perhaps scientific literacy, the term, educational technology describes the technological tools that teachers use to help students learn any subject, i.e. computers, digital projectors, interactive whiteboards, and programmable calculators. This confusion leads many teachers to believe that they are teaching their students about technology, when they are only exposing their students to computer applications for educational purposes (Pearson & Young, 2002).

The National Academy of Engineering (NAE) definition of technological literacy will be used in this paper (Pearson & Young, 2002). The NAE states that a technologically literate person is one who recognizes technology, understands the difference between science and technology, knows some basic concepts about technology, understands the goals and trade-offs implicit in the engineering design process, recognizes how technology has influenced society through the ages, and as well recognizes how society has also shaped technological advances, understands that using technology entails risks, and that all technology has both benefits and costs. A technologically literate person understands that technologies are neither inherently good
nor evil, and that the values of a culture or society are reflected in the technologies that
the culture or society embraces. A technologically literate person should have some
hands-on skills with tools and devices so that he or she has the ability to diagnose and fix
certain problems such as a flat tire or a tripped circuit breaker, and finally, a
technologically literate person should be able to participate in public debates and
discussions about technological issues, and cogently communicate his or her ideas about
technology.

In order to promote scientific and technological literacy, reform efforts in science
education stress a change in emphasis toward active, inquiry-based learning. The active
process of learning involves both mental activities and physical activities as students
work with their teachers and peers (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. Dramatically demonstrated in the documentary,
*A Private Universe*, even some Harvard graduates and professors cannot explain why the
Earth has seasons or why the moon has phases (Schneps & Sadler, 1988). Several strategies have been researched to help people work through these invented theories and develop more scientific understandings, but the process of conceptual change is difficult for teachers and students alike (Posner, Strike, Hewson, & Gertzog, 1982). The science content focus of this study is heat transfer and thermal energy.

Science Definitions

Heat transfer and thermal energy

Considering the different conceptions students and adults alike have about thermal energy and heat transfer, the following formal scientific definitions of these constructs- as used in this study, are prudent to document.

Thermal energy- Thermal energy exists when molecules are in motion; when the atoms or molecules in a substance vibrate. They have kinetic energy, which creates thermal energy. The amount of thermal energy something has is the sum of the kinetic energy of all the particles. That is why a bathtub of water has more thermal energy than a sink of water when the water is the same temperature in both. As something loses thermal energy, these molecular vibrations slow down. As something gains thermal energy, these vibrations increase. If enough thermal energy is added to a substance, the vibrations may even cause a solid material to lose its form and melt, or a liquid substance to evaporate, or a gaseous substance to expand as the distance between particles increases. Thermal energy can be transferred from one place to another when there is a temperature difference.
Heat transfer- Heat transfer is the transfer of thermal energy through conduction, convection, or radiation. It always occurs from a place where there is a higher temperature to a place where it is cooler. Heat transfer in a bathtub occurs from the hot water to the cooler air and to the cooler person in the water. Heat transfer in a freezer always occurs from the unfrozen items placed inside it to the colder air in the freezer. Heat is not a stored quantity that can be measured like thermal energy can. Heat is by definition energy in motion.

Conduction- Conduction is the way thermal energy transfers from one substance to another by direct contact. It can be the direct contact between solids, or between a solid and a fluid. Kinetic energy is transferred as higher temperature vibrating molecules or atoms collide with cooler matter, increasing the kinetic energy of the cooler substance.

Convection- Convection occurs when moving fluids (gases or liquids) rise and fall due to differences in density caused by differences in thermal energy. In this way, thermal energy is moved from one place to another through the bulk movement of fluids.

Radiation- Radiation is the transfer of energy in the form of electromagnetic waves. Visible light and infrared light are both forms of radiation that transfer thermal energy. Heat is transferred from the Sun to the Earth through radiation. Heat is transferred from a microwave oven to food through microwave radiation.

Insulator- An insulator is a material which reduces the rate of heat transfer, therefore it reduces the rate at which thermal energy moves from a warmer place to a cooler place.
Addressing students' conceptions about heat transfer and thermal energy

Active learning – tangible engagement with scientific phenomena – may be one successful strategy for addressing students' alternative, or non-scientific, conceptions in science (Brown, 1992; Vosniadou, Ioannides, Dimitrakopoulou, & Papademetriou, 2001). Much research points to the positive effect of active learning methodologies such as problem-based learning, cooperative learning, and collaborative learning, on academic achievement (Prince, 2004). Active learning provides an environment conducive for conceptual change and can involve students participating in projects, solving problems, designing experiments, voicing their ideas and listening to the ideas of their peers (Vosniadou et al., 2001). One type of active learning – design-based science – involves students in engineering design problems where they design, build, and test devices as a means to develop scientific understandings and technological literacy. However, virtually no research exists to demonstrate whether the active learning methodology of design-based science has the potential to help students with persistent alternative conceptions restructure their knowledge about scientific phenomena.

Design-based science

Design-based science falls under the pedagogical umbrellas of problem-based learning and project-based learning. Since these terms will be used frequently throughout this paper, it is important to define how they will be used.

Design-based science is an offshoot of project-based science, which is an offshoot of problem-based learning. Problem-based learning (PBL) is a pedagogical tool whereby
students learn any type of content in the context of real-world problems. The teacher or student develops the nature of the problem, and then students work in small groups to find information, learn concepts, and come up with a solution to the problem. Problems can be science related, but are often business, medical, or engineering related (Savery & Duffy, 1996).

Project-based science is similar to PBL because students are solving problems in collaborative groups, but the content is science-based and the problem is solved and the solution presented through the creation of a project of some type: a video, a presentation, a poster, or a website (Krajcik & Czerniak, 2007).

Design-based science is a type of project-based science, but the solution is typically a designed, built, and tested three-dimensional device which necessitates the application of scientific knowledge. The solution can also be a two-dimensional drawing or a computer model generated with Computer Aided Design (CAD) software.

Problem Statement

Middle school students have been the target of many engineering outreach programs throughout the United States. Over 50 different outreach programs for pre-college students are currently active in the US. These engineering programs and projects come from professional organizations, universities, or industry. One outreach program, Project Lead the Way (PLTW), a nonprofit organization that provides engineering curriculum to middle and high schools, has been used in more than 2200 schools across the country.
The curriculum used in this study is derived from an engineering outreach program at the University of Virginia, the Virginia Middle School Engineering Education Initiative (VMSEEI). Dozens of engineering design-based curricular kits have been developed by the VMSEEI and used in hundreds of classes and workshops, but until now, none have undergone rigorous evaluation in terms of their impact on students’ science conceptions and engineering attitudes.

The engineering design process espoused by the VMSEEI Engineering Teaching Kits (ETKs) encourages students to apply scientific concepts as they engage in design challenges that let them create artifacts that form solutions to problems. Design is a core function in engineering, and a key component of technology education and technological literacy (Pearson & Young, 2002). Even though much time and energy has been spent developing engineering outreach programs like PLTW and ETKs, there is a paucity of research on how effective they are at helping students actually learn important science concepts and develop more positive attitudes toward science and engineering (Chaker, 2008). Additionally, there is virtually no research on how engineering design activities might promote conceptual change in science. While many outreach programs adequately promote technological literacy and an interest in the field of engineering, the degree to which they support scientific literacy and deep conceptual understanding is an ongoing question. The methods used to assess these engineering outreach programs often do not include assessments of science knowledge, and if they do, the instruments used to do the assessing are often not demonstrated to be valid or reliable instruments. The research methodology is often quantitative, leaving out answers to fundamental questions of how
students’ conceptions might actually change throughout the process of designing, building, and testing. How middle school students learn meaningful science through this design process, reformulate their alternative conceptions of science, and change their attitudes toward science and engineering will be the main topic of this thesis.

The purpose of this study is to investigate how engineering design activities can be used to foster standards-based scientific content understanding, technical skills, and conceptual change, while encouraging interest in science and engineering. Specifically, the study looks at how middle school students working in small collaborative groups on one engineering-design activity about thermal energy and heat transfer can subsume the need to understand science concepts related to heat, providing them with a context in which to learn, and a rationale for learning science in an active, inquiry-based method. This study focuses on questions of “how” as opposed to questions of “if” (Ferguson, 2007). The study is planned to study how students construct knowledge about thermal energy and heat transfer, and how they develop attitudes toward and understandings about engineering. The objective is to see things from the participants’ points of view, furthering the quest to discern “how.”

The major research questions guiding this study include:

1) How might students’ conceptions about thermal energy and heat transfer differ before, during, and after engineering design-based instruction and typical instruction on the topics of thermal energy and heat transfer?

2) How might students’ conceptions about and attitudes toward engineering differ
before, during, and after learning heat transfer and thermal energy through an engineering
design challenge?

3) How might an engineering design challenge specifically change students'
conceptions of thermal energy and heat transfer?

This study will be carried out through the use of an Engineering Teaching Kit
called *Save the Penguins* developed through the Virginia Middle School Engineering
Education Initiative. The objective of this ETK is to have students design, construct, and
test a device which will keep a penguin-shaped ice cube from melting. The ETK will be
described in detail in Chapter 3.

**Significance of the Study**

Participating in engineering design activities is part of the global definition of
scientific literacy put forth by the *Benchmarks for Science Literacy*. "By participating in
such activities, students should learn how to analyze situations and gather relevant
information, define problems, generate and evaluate creative ideas, develop their ideas
into tangible solutions, and assess and improve their solutions" (AAAS, 1993, p. 48).

Students are not blank slates; they come to science class with all sorts of
preconceived ideas about the way the world works. Through engineering design, students
have the potential to test their preconceived ideas and see how their ideas either stand up
to empirical scrutiny or fail. In addition to answering questions about how engineering
design impacts students’ attitudes toward science or engineering, this research will
answer an important question about the potential engineering design has to address
scientific literacy by helping students restructure tenacious alternative conceptions about
Science, specifically those concerning heat, temperature, and heat transfer. This in turn can inform the development and improvement of other engineering design curricula so that alternative conceptions are elicited prior to the instruction, and targeted through appropriate activities.

Engineering design is an active learning methodology that science teachers can use effectively if the curricula are well designed and described, and if teachers are prepared teach through design. The National Center on Education and the Economy stresses in its report, *Tough Choices or Tough Times*,

The American economy will not succeed in the circumstances we foresee unless people at every level of our society are accomplished, original designers. And that will not happen until design – good design – plays a much larger role in the American curriculum (National Center on Education and the Economy, 2007, p.30).

Curricular materials do exist, but few are tested by research to see if they work effectively to achieve particular objectives. The research is not equivocal, and more solid evidence is needed to investigate how design activities can not only engender more positive attitudes toward science and engineering, but enable students to learn significant science at a deep conceptual through engineering design problem solving. Universities, corporations, and non-profit groups have invested considerable effort and money to create engineering outreach programs; however it is cautionary to include these programs in science classes, or prepare pre-service science teachers to use the materials, unless empirical support exists to demonstrate that they truly do more than expose students to career options.
If engineering design does indeed have the capacity to improve student attitudes and help students achieve scientific literacy through the restructuring of alternative conceptions of science, then researchers and educators can be more confident that this active-learning methodology has merit and is worth pursuing. However, if engineering design is found to have negligible impact on students’ science conceptions or their attitudes toward science or engineering, then science educators may want to consider engineering design in science classrooms as an adjunct to the curriculum, serving a limited purpose. This is an uncomfortable position because stakeholders truly want to believe that engineering design curricula make a difference. Either way, this research has the potential to inform researchers, teachers, and teacher educators about the limitations and/or benefits of active learning through engineering design.
CHAPTER 2: REVIEW OF THE LITERATURE

Introduction

The literature reviewed in this chapter pertains to both the subject and the methods of the proposed research. The proposed research is intended to evaluate the use of a design-based science activity in order to help middle school students learn about heat transfer. Therefore, this chapter begins with a description of design-based science and 16 studies that have used this intervention technique to teach a variety of science content topics. It follows with a description of four studies that have revealed the alternative conceptions children frequently have about heat and temperature, and concludes with a description of four interventions used to address those non-scientific conceptions, and a summary of all 24 studies reviewed.

Problem-based Learning

Before reviewing the literature on design-based science, it is important to describe the methodological and theoretical roots design-based science has in problem-based learning. Problem-based learning (PBL) is just one member in the family of active learning methodologies based on the theoretical framework of constructivism (Piaget, 1980; Vygotsky, 1978). The instructional principles of constructivism imply that learning activities are anchored within a larger purpose, that the learner takes ownership for his or her goals in learning, and that the tasks are authentic. The learner does not merely memorize and regurgitate facts, but engages in authentic activities related to the
instructional goals. Learners use all sorts of resources and sources of information to support their inquiry. Students take ownership for learning and problem solving, while a teacher encourages and challenges the pupils. Teachers take on the role of consultant or coach, challenging the learners as well as valuing their process of learning. The teacher does not tell the students how to think or what to do (Savery & Duffy, 1996).

PBL has been used in a variety of educational settings, but it received its start in the mid 1950s in North American health sciences education. It emerged as an ethical and practical way to give beginning medical students practice solving problems in simulated cases before working with actual patients. Programs at McMaster University in Canada and Case Western Reserve University were the forerunners to what we call PBL today (Boud & Feletti, 1997). Problem-based learning has been used in over 60 medical schools in addition to business schools, schools of education, as well as schools of architecture, law, and engineering (Savery & Duffy, 1996).

When students engage in problem-based learning, problems relevant to the curriculum provide the context and motivation for all the activities that follow (Barrows & Tamblyn, 1980). This form of active learning is usually cooperative or collaborative, and students within a group do not compete against each other. Learning is self-directed to a significant degree (Prince, 2004). It is not achieved by merely adding problem solving to the curriculum. The entire curriculum is centered on relevant problems. Students learn skills and facts as they progress through the process of solving the problem (Boud & Feletti, 1997).
Instead of making sure that the students have all the knowledge and skills they need to solve a problem before it is posed, PBL has students identify and seek out what they need to know by themselves. The problems can be posed by either a teacher or team of curriculum designers, or the problem can be posed by student groups or individual students. The problems are usually selected with particular goals in mind: either to make sure students end up covering a field of knowledge, or to make sure students become familiar with solving problems typical to their field of study (Ross, 1997).

Problem-based learning has been used in K-12 schools. With PBL as the teaching methodology, the teacher is not considered to be the main source of and disseminator of knowledge; she is a guide in the learning process. She is also a model for the students, modeling how to think and learn, scaffolding students’ learning. Self-directed learning is a key emphasis in distinguishing PBL from other teaching methodologies. In problem-based learning, the learners are immersed in a particular, practical context, often a student-chosen context. One goal of problem-based learning is to help students develop an intrinsic motivation to learn. Since students are more motivated to learn when they see value in what they are learning, it is important that students or teachers choose problems that are relevant for the students (Hmelo-Silver, 2004).

Problem-based learning encourages students to think critically, analyze and solve complex problems, seek out and find resources for learning, work together in cooperative groups, polish communication skills, and learn to become lifelong learners. Students continuously evaluate what they know and what they need to know in order to understand and solve a problem. Communities of learning are created in the classroom (Duch, Groh,
& Allen, 2001). Students are encouraged to be open-minded, critical, and active learners. Students and teachers are each respected as shared partners in learning (Margetson, 1997).

Overall, studies on medical students reveal that PBL has a positive effect on student attitudes (Vernon & Blake, 1993). However, there is some difficulty in assessing knowledge gains when students are instructed through PBL because many of the concepts students learn from PBL, like problem solving and life-long learning, are difficult to measure (Prince, 2004). Additionally, while much research has focused on problem-based learning in medical education, very little research on problem-based learning has taken place in K-12 classrooms (Scott, 2005).

Design in the Science Classroom

Design-based science is a form of problem-based learning where the design, construction, and testing of a device solves the problem. Design is to engineering what inquiry is to science. They are both problem-solving activities that use cognitive reasoning, mental models, evaluation, rely on content knowledge, and operate within constraints (Lewis, 2006).

Design-based science activities center on a student-designed, built, and tested artifacts. Students learn scientific principles on a need-to-know basis as they strive to design a device (an artifact). Design became a topic of discussion in science education in 1993 when the American Association for the Advancement of Science published *Benchmarks for Scientific Literacy*. The AAAS stated that while design projects are
common in the elementary grades, all students should become familiar with design and technology projects in order to engage in problem-solving in real-world contexts. They recommended that:

Perhaps the best way to become familiar with the nature of engineering and design is to do some. By participating in such activities, students should learn how to analyze situations and gather relevant information, define problems, generate and evaluate creative ideas, develop their ideas into tangible solutions, and assess and improve their solutions. (p. 48)

While this recommendation was not exactly design-based science, because design is not used as a conduit through which students learn science, the AAAS did state that teaching design should not be the sole responsibility of technology teachers; science, math, and even social studies teachers should share this responsibility.

The National Research Council followed suit in 1996 with its own recommendations on how science should be taught. The NRC’s (1996) National Science Education Standards included an emphasis on students’ abilities to design solutions to problems in much the same way that inquiry is conducted to answer research questions. The NRC stated that young children should be conducting design activities. “Children can engage in projects that are appropriately challenging for their developmental level—ones in which they must design a way to fasten, move, or communicate (p. 135).” This recommendation comes closer to design-based science because the NRC recommended that design tasks should be related to other science content standards. In an example on pages 162-164 called, “The Egg Drop”, the reader is taken through an example of how a design challenge can be used in a science classroom. As opposed to how design-based
science is construed today, student engaged in this activity are frontloaded with science definitions and concepts such as force, motion, gravity, and acceleration. These concepts are then applied as students construct the egg-drop devices. Design activities are linked to science concepts, but true design-based science did not emerge until later that year when Roth’s (1996) study of elementary school children immersed in a civil engineering-based unit was published in *The Journal of Learning Sciences*.

**Design-Based Science**

This section contains reviews of 16 studies done in the field of design-based science since its inception in the mid-1990s, organized chronologically within three categories: a) research on the design of structures, b) research on the design of models, and c) research on virtual designs. The majority of studies conducted on design-based science have students actually designing, building, and testing structures, although 2 of the 11 studies in this first category have students design on paper or on a computer. Results and methodologies are mixed. While some studies report positive findings, the important question is, “positive for what?” Many researchers only tested one construct, and with dubious instruments, yielding dubious results.

**Research on the Design of Structures**

Most of the research on design-based science has students designing functional structures. Students can engage in the design of structures at any age while learning any science content, however topics related to physical science dominate the literature. Designing physical structures comes very naturally to most children- as natural as
Roth (1996) was working with a pair of elementary school teachers and their one class of 29 fourth and fifth grade pupils in British Columbia, Canada, as they became immersed in a 13-week unit on structures. The curriculum, called *Engineering for Children: Structures*, was designed by one of the teachers for the Canadian non-profit group, Association for the Promotion and Advancement of Science (Roth, 1995). Through an open-ended process, students worked with partners of their choosing to design, build, and test towers, bridges, and domes. The children in this study were learning science through the design process. They were working with loosely-defined problems in authentic environments, which allowed them to experience a community of practice with socially constructed knowledge mediated by expert peers, teachers, and others. Roth directly observed and videotaped lessons, took field notes, interviewed students and teachers, and examined students’ engineering logbooks which consisted of design ideas, drawings, photographs, reflections, and definitions. He gave a pre- and post-assessment which consisted of the open-ended question, “Engineering is ____”, to which students wrote text or drew pictures. Additionally, the results of a pre-assessment challenge to build a bridge from a single sheet of paper were contrasted with the final bridge design challenge. Discourse, conversational, and interaction analyses further enriched the data corpus.

Roth worked within the theoretical perspective of situated cognition, which seeks to explain knowledge as a product of the context, activity, and culture of the learner (Brown, Collins, & Duguid, 1989). He found that while children claimed sole authorship
of their designs, the entire learning environment contributed in fundamental ways. The
tools and materials available, teacher and peer influences, even current and previous
states-of-design contributed to the final products.

In keeping with the philosophy of situated cognition, the design processes did not
emerge from solitary ideas and skills, but were situated within the interactions of the
community, the materials and tools at hand, and the current and past states-of-design. He
found that the process of design gave students a way to integrate thinking in the abstract
with acting in the concrete. The students learned how to cope with the complex nature of
open-ended design, their self-confidence grew, and they learned to think flexibly about
tools and materials, putting them to new and creative uses. They learned about the
process of design, how to negotiate with one another, and how to write and communicate
ideas about engineering design. They did not learn merely a collection of facts and
definitions related to civil engineering constructions, they learned a broad variety of
concepts through a set of meaningful experiences, set in context. “The collective design
of artifacts is a powerful context of learning because it allows children to unload
cognition into the physical and social environment (p. 161).”

Roth did not directly assess students’ science content knowledge related to the
physics of structures, although he expected that the design activities would help the
students learn about properties of materials, forces, simple machines, energy, and work.
He implied that traditional evaluation of student performance and learning is difficult in
design environments, and that constructing artifacts does more for students than merely
motivate them to learn; it gives students valuable problem-solving experiences in ill-
structured settings. This study is considered to be one of the seminal examples of research on design-based science, however an evaluation of science knowledge was neither planned for nor executed.

Australian educators McRobbie, Stein, and Ginns (2000) found that students engaged in design activities did not implicitly learn science principles. Their study involved students in two sixth grade classes, challenged to build self-propelled model boats. A pre-cut hull and a variety of building materials were provided to each group of student teams. Primarily, students learned about the design process, with “little explicit knowledge...developed about the natural world, that is, knowledge about the properties of materials, and scientific and engineering knowledge related to the task at hand (p.11).” The researchers concluded that teachers who incorporate design into the classroom with the goal of teaching science must find a balance between creating authentic design challenges and assisting students in their understandings of scientific knowledge. They proposed that teachers intervene at appropriate times to help students acquire richer understandings of the natural world. It was not clear from reading this study how long students were involved in the design activity, nor was it clear how any science knowledge students may have acquired was assessed.

Seiler, Tobin, and Sokolic (2001) conducted a study on design-based science in an urban high school designed for at-risk students. Attendance hovered around 50%; almost all students lived in poverty and had been removed from other high schools for failure or violence. While there were 33 students enrolled in the class, median daily attendance was 15. The researchers were specifically seeking to learn whether an active-learning science
Students in a physical science class were challenged to design, build and test small model cars that were to be powered by the exhaust from an inflated balloon. This design activity was part of a larger unit on Newton's laws of motion. Researchers noted some initial concern because the design task was imposed on students, not chosen by them. The study took place during five 75-minute class periods, which were co-taught by the second and third authors, Kenneth Tobin and Joseph Sokolic. The first author, Gale Seiler acted as participant observer, collecting qualitative data while assisting students as necessary. Qualitative data was collected through audiotaped discussions, videotaped classes, observation notes, collected student artifacts, and a follow-up interview with one student. The researchers used discourse analysis to examine their data and develop categories for discourse types.

Students were given a set kit of materials from which to build their cars, with the exception being the wheels. Students were expected to bring soda bottle caps to school for car wheels, and many consistently failed to do so.

Students measured distance and time, calculated velocity and discussed acceleration, friction, force, and other relevant concepts with teachers and researchers. The students were deeply involved in the project, but through a close analysis of student discourse, researchers realized that even though a great deal of design-related discourse occurred, scientific vocabulary was not part of typical discussions. Even display posters that students created did not contain references to Newton's laws. Much of the discourse...
that went on in the classroom had to do with perceived respect from peers. It was not “cool” to play with cars, to be perceived as an achiever, or to step out of stereotypical gender roles. Males were especially reluctant to participate, and often ridiculed those that did choose to participate. Students became possessive over shared materials such as tape, scissors, straws, and bottle-cap wheels. While discourse was not teacher-centered and students were constantly talking with one another, attempts to direct the whole class through teacher-centered discussions were fruitless, and teachers were commonly treated with disrespect. The researchers concluded from this study that one-size does not fit-all when it comes to science teaching and learning, and that educators need to find ways to reach students with methods that match the circumstances. “The activity failed because it neglected to take into account the historical and social environments in which the students live and attend school” (p.761). Respect was the currency in this classroom, and since respect was not shared between all classroom members, including teachers, science as inquiry-active learning-could not occur. This study resulted in some interesting findings about how teachers need to establish respect and rapport within the classroom and work with the cultural norms, not against them.

Roth (2001) continued his research on design-based science working as a teacher-researcher for 4 months with a combined sixth and seventh grade science class (10 sixth graders and 16 seventh graders) that he taught at a suburban school in Canada. It was a difficult class to work with, as many of the students had academic, personal, family, language, or social problems. The curriculum centered on simple machines, and Roth devoted 60% of class time to student design of machines. Students designed pulley
systems, devices that were similar to ski lifts, and other machines that needed to move heavy loads. The remainder of class time was devoted to whole-class discussions and small-group investigations. Students were tested before, during, and at the end of the unit. Additionally, they were interviewed as often, and videotaped throughout the entire unit. All class artifacts were collected for analysis as well. An additional observer was present during classes, and each class was discussed by a research team afterwards. Roth stated that space did not allow for a proof of his claim that “technological activities provide an ideal context for learning science (p. 775),” but instead described examples to support his claim and directed the reader to a book he co-authored for more examples (Roth, Tobin, & Ritchie, 2001).

Roth felt that an important part of his students’ designing technological artifacts was drawing and explaining the designs. He provided an example of how difficult it was for one particular student to explain his design until he got up from his seat and drew it on the chalkboard where it could be “inspected, critiqued, and argued about” (p. 777). Another key element in Roth’s opinion was the act of building prototypes. The shift from thinking, discussing, and drawing to building artifacts that served to externalize ideas made ideas accessible and easily built upon.

Students found it difficult at first to be learning in an active way; they were used to lecture-style classes, and had trouble articulating themselves. The designed artifacts made it easier for students to engage in discourse since they had something concrete to refer to. Roth purported that the artifacts actually freed up mental resources for the students, as they were able to partially move their thinking into the concrete world. He
also stated that students were able to communicate with more complexity when they had physical objects to assist them. Roth compared this relationship between mental models and physical ones to the cardboard double helix model of DNA created by James Watson, and concluded his article by stating that technological activities are very suitable for integrated science learning. He did not provide much data beyond some excerpts from classroom observations, did not include a control group, and referred the reader to dozens of his other published studies for more information.

At the University of Michigan, Mamlok, Dershimer, Fortus, Krajcik, and Marx (2001) developed a design-based science curriculum called Learning Science by Designing Artifacts (LSDA), a curriculum based on the theoretical framework of social constructivism. They described social constructivism as involving active engagement, contextualized learning, community building, and disciplined discourse. They described design-based science as a form of problem-based science in which students design physical artifacts that solve real-world problems. The artifact design is not the culminating activity, but is the actual structure around which all learning is organized. Additionally, the LSDA curriculum incorporates the use of primary source documents and computer technologies. Ironically, in this particular study, the only artifacts students created were posters.

When the LSDA curriculum was initially introduced into high school science classrooms, the researchers found that while the students enjoyed the activities and lessons, not enough time was dedicated to science concepts. They began to re-design the curriculum with the goal of improving science content understanding without taking
away from the positive attitudes students had towards the curriculum. Studies of the two iterations of this curriculum were described.

In this study, 75 students were taught by 2 teachers (1 experienced and 1 inexperienced). They were exposed to current debates about the safety of cell phones, and challenged to design safer cell phones. The students got involved in research on the Internet and through a series of labs they learned about batteries, sound, electromagnetic radiation, and even surveyed teenagers about their cell phone use. The unit of study was described as a multi week unit in a science 'elective' course that all students in the ninth grade were required to take. The study was conducted for two different semesters, thus with two different groups of students. The first semester group had 9 weeks to complete the course, while the second semester group only had 5 weeks due to schedule changes.

Both a science attitude questionnaire and a science content test were given pre- and post-instruction. Both instruments were based on previously published work. The attitude questionnaire consisted of 15 semantic differential scales about the term, "science" which was construct validated by factor analysis, and 47 Likert-scale items about science in general covering 12 different constructs about science attitudes and motivation. The content test consisted of 15 multiple choice questions and five open-ended questions. During the first semester, 50 students participated. Results of a paired t-test on the science attitude questionnaire revealed positive change in attitudes over the course of the semester ($p < .05$) on some of the questions, and no significant change on other questions. Means and ranges of scores were not reported. A comparison of means on pre- and post-content tests indicated a significant increase in understanding ($p < .001$)
with an effect size of 1.44. The pretest mean was 4.10 and the posttest mean was 6.70 out of 15 possible points. No other information about reliability or validity was reported on either instrument.

During the second semester, there was no significant difference in science attitudes between the beginning and end of the semester. There was a significant increase in content test scores over the semester \( p = .001 \) with an effect size of .651. The pretest mean was 7.70 and the posttest mean was 9.57 out of a possible 14 points since one test item was eliminated. There were no statistical tests run to measure differences between the two semesters. The researchers concluded that their redesigned curriculum taught the second semester was superior to the first semester curriculum because more science content was covered without a loss of interest in science. However, the researchers pondered why the content posttest scores were not higher given the increased emphasis on content. They concluded that the lack of random assignment played a key role; students in the second semester course were higher achievers and had higher pre-test scores. They also concluded that the second semester participants had already completed a first semester of ninth grade science, and thus had more content knowledge. They also stated that the inexperienced teacher was not adequately prepared to teach the more challenging content in the second semester; during the first semester, the course was team taught by both teachers. Finally, the students had less time to complete the unit: 5 weeks in the second semester instead of 9 weeks. Obviously, the participants in the different semesters received very different treatments and this study was fraught with confounding variables.
The researchers also compared the attitude posttests, and stated that the attitude posttest mean was 3.88 after the first semester on a 5-point Likert scale with 5 representing positive science attitude, but only 2.65 after the second semester. They concluded that since students in the second semester course were not as interested in science, they may not have wanted to put in the effort necessary to master the increased content demands, or they may have found it too easy. There was no qualitative data presented to help the reader discern these questions, nor was there enough information about the design challenge to adequately judge the design-based science interventions. The fact that students only designed and never built or tested their ideas may have played a role in their attitudes as well.

A 2003 study by Kolodner, Gray, and Fasse looked at how their Learning by Design™ (LBD) program enabled middle school students to transfer their problem-solving knowledge and skills to novel situations. The researchers examined a wide variety of situations during which transfer of knowledge and/or skills could take place. They observed standard-level and honors-level groups of students transfer what they had learned about structures from one 8 week LBD unit called Vehicles to another called Launcher. They observed individual students transfer knowledge from their LBD experiences to the task of completing a science fair project. Finally, the research team administered a performance assessment to both students who had participated in LBD units (the LBD students), and control groups of students of similar achievement abilities. Students were asked to follow an experimental procedure in order to test different types of tire materials on different types of road conditions and measure the force needed to
overcome sliding friction. The assessment tasks were videotaped for analysis. Students worked in groups but the number in each group was not reported. A variety of student behaviors were measured, such as the use of scientific terminology, collaborative negotiation, explication of prior knowledge, etc. For two school years, classes of "typical" students were compared to each other, and classes of high achieving students were compared for both LBD students and control-group students. The researchers scored the student teams on a variety of constructs, giving them an overall score on a scale from 1 to 5. These constructs were: self-checks during experiments, science practice of designing and running experiments, distribution of the tasks, negotiations during collaboration, adequacy of prior knowledge, and use of science terms. The number of classes and the number of students in each class were not described. The methodology for inter-rater agreement for this assessment process was not described; however validity of the scoring scheme was implied when the researchers compared the scores from students in LBD classes to those of students in control-group classes.

In this study, t-tests were performed to compare the performances of different classes in these constructs during two school years. Statistically significant results showed up in the areas of self-checks, science practice, distribution of efforts, and negotiations during collaboration, but not in adequacy of prior knowledge and use of science terms. The unit of analysis in this study was a class of students, not individual students. Not only were there statistically significant differences with LBD classes outperforming control-group classes, but LBD students in typical classes outperformed high achieving students in the control classes. For example, in the construct, "science
practice of designing and running experiments", standard level students in the control group scored 2.25 (out of 5), while standard-level students in the LBD group scored 2.75. Honors-level students in the control group scored 2.67 while honors-level students in the LBD group scored 4.75. The difference between honors-level student groups was significant at $p < .001$ but the researchers point out that students in the standard-level LBD course scored higher than students in the honors-level control course. This pattern repeated itself over 2 years of the study with most of the constructs tested. Kolodner and her team concluded that LBD students were better at transferring their knowledge and skills to novel situations than the control groups of students. The researchers stated that their data indicate that LBD students were better at collaborating with their peers in the "practices of scientists" than control-group students. They suggest that teachers use the scientific vocabulary that they want their students to use and that they model the behaviors that they want their students to engage in. Additionally, the researchers suggest that teachers model how to cognitively reflect after an activity so that students will be better able to successfully carry out that skill. The performance assessment did not directly assess science content knowledge gains.

In 2004, a study was published by the same University of Michigan team (Mamlok et al., 2001) that developed the design-based science curriculum in which students designed cell phones but never constructed anything. In 2004 however, Fortus, Dershimer, Krajcik, Marx, and Mamlok-Naaman (2004) called their pedagogy, Design-Based Science (DBS), and artifact construction became part of the curriculum. They studied 92 ninth and tenth grade students in three different physical science classes who
had participated in three consecutive DBS units of study. In each unit, the design challenge was at the heart of the curriculum, not a culminating application of science concepts learned through other means. The design was the vehicle through which learning took place. The first unit was called, “How Do I Design a Structure for Extreme Environments?” with the goal being the construction of a well-insulated model house. This unit was studied for 8 weeks, 5 hours a week. The second unit was called, “How Do I Design a Battery that is Better for the Environment?” with the goal being the construction of a safe wet-cell battery. This unit was studied for three and a half weeks, 5 hours a week. The third unit, called “How Do I Design a Cellular Phone that is Safer to Use?” was previously described by Mamlok et al. (2001). It was studied for 6 weeks, 5 hours a week. Each unit contained several learning cycles with each cycle focusing on a different content area relevant to the design. A key element of the DBS curriculum was the DBS Learning Cycle. The first step was setting the context for the challenges. The second step involved background research, which took the form of group experiments, reading assignments, lecture, or teacher-led demonstrations. The third step was for individuals to set personal goals, and then share those goals with the small working group. The group decided together which solutions to pursue while the teacher critiqued each group. The fourth step involved creating artifacts. The small group of four splits into pairs, and each pair constructed a model of the design solution. After each pair has constructed a model, the group rejoined to discuss and compare. They collectively decided on the superior model. The fifth step in the learning cycle was designed for students to both provide and receive feedback. Pin-up sessions similar to those suggested...
by Kolodner et al. (2003) allowed other students and the teacher to move about the class and critique one another. After feedback, students could revisit any step in the learning cycle for further revision.

Students were given pre- and posttests on science content for each unit. The assessments combined multiple-choice with open-ended questions. Reliability and validity data were not provided about the assessments, which were developed by the research group. These tests consisted of both multiple choice and open-ended questions. Inter-rater reliability was measured to be 99% for assessing these tests. Students also created models and posters in the process of their design challenge. These artifacts were also scored by the researchers or the teacher with a detailed rubric, and inter-rater reliability was deemed to be 99%.

The researchers computed independent sample t-tests on the pretests of science content to ascertain whether student groups differed from one another pre-instruction. The results indicated that the groups were not statistically different from one another pre-instruction. For the Extreme Structures unit, $p = .650$, for the Safe Batteries unit $p = .830$, and for the Safer Cellular Phones unit $p = .830$. The researchers conducted paired sample t-tests to ascertain whether gains were made over the course of the three units of study. For the structures unit, $p < .001$, with an effect size of 2.1. The pretest mean was 7.9 out of 23 points and the posttest mean was 14.7. For the battery unit, $p < .001$ with an effect size of 1.9. The pretest mean was 6.8 out of 22 points and the posttest mean was 11.9. For the cellular phone unit, $p < .001$ with an effect size of 2.7. The pretest mean was 4.0 out of 21 points and the posttest mean was 11.2. In all cases, students performed
significantly higher on posttests than pretests, basically doubling or more than doubling their scores.

The models were evaluated on dozens of criteria, and the researchers concluded that students learned a substantial amount of scientific knowledge that they were able to apply. One concern about the cellular phone unit is that students did not actually build any devices; they created 2-D poster representations of what they would build. A larger concern is that this study did not include a control group, so it is not possible to compare the learning gains by these students to students in traditional classrooms.

By the time that Puntambekar and Kolodner (2005) wrote their most recent article for the *JRST*, the Learning by Design™ group at Georgia Tech had developed a year's worth of design-based science units for both physical and earth science at the middle school grade level. They were attempting to answer new questions related to design-based science, specifically how to best help students successfully learn scientific reasoning through better scaffolding. "There has not yet been a systematic study of how to design and implement scaffolding in a classroom that takes into account the original tenets of the notion of scaffolding and adapts it to the changed context of the classroom (p. 190).

However, with one teacher and many students at different levels of development, this was a daunting task. Students needed several forms of support during class. The research team learned that a computer tool can provide some scaffolding support. They learned that the use of design diaries provided another form of support. The design
diaries were not full of blank pages, but contained prompts to assist students in the learning process. They provided hints. They made the thinking process visible.

Puntambekar and Kolodner tested the idea of using design diaries with 4 groups of eighth grade students (for a total of 109 students) and an experienced PBL teacher. As students worked through the 3-week PBL unit, *Jekyll Island Challenge*, they used their design diaries too, either in class or at home. At the end of the unit, the diaries were collected for analysis. This analysis was coupled with observation notes taken by the first author, who attended two of the four classes each day. The diaries were coded by two researchers with an inter-rater reliability of 90% in different categories on a scale of 0 to 3. The diaries were examined to see if students’ scores progressed over time. A Wilcoxon signed-rank test was used to analyze the progression of students’ scores over time. Some students did progress while an equal number actually regressed and the rest did not change. Neither scores nor statistics about scores were reported.

The students missed many opportunities to connect science to their designs. They did not get into the habit of referring back to the diaries in the manner the researchers intended. They didn’t share their diaries with one another, and questions in diaries did not emerge in group or class discussions. Students were using the diaries as homework assignments and did not take advantage of using them in class to the degree they could have. The teacher was not checking these diaries along the way, so she was not aware of some issues going on. The diary use was not well integrated with the rest of the activities.

The research team learned from this study that the design diaries needed to be
more integrated into the activities. The diary prompts needed to be more specific. Time needed to be set aside for diary sharing. So, they refined the diaries and implemented their use again one year later. They also added the use of pin-up sessions and periodic whole-class discussions. During the following year at the same school with the same teacher, the researchers worked with another set of 8th grade earth science classes on the same unit for 5 weeks, which was 2 weeks longer than the first year. The new diaries were used, whole-class discussions became more frequent, and students shared their ideas with one another more frequently. The design diaries were analyzed at the end of the unit, just as they had been during the first year. However, this time there was a marked and statistically significant increase in the use of scientific knowledge to justify design decisions. Students had better insight, and wrote about more questions that they had, and they progressed more throughout the process with a significant difference in scores from the beginning to the end of the diaries as indicated by the Wilcoxon signed-rank test ($z = -.308, p < .001$). Means were not reported, but there were 34 positive ranks and only 8 negative ranks where a positive rank indicates a shift from a lower score to a higher score. The difference between the two groups was also statistically significant. The researchers admitted that the differences between the two groups (the first and second implementation of the DBS unit) were great enough that it was impossible to definitively state causes for the changes, but that nevertheless, they learned some things about the kinds of support students needed while doing design-based science.

The Museum of Science in Boston has developed a curriculum called Engineering is Elementary (EiE) with 10 separate units for elementary school-aged children. Each unit
contains a story, lesson plans, and a culminating design challenge. The goals of the EiE program are both to teach children about engineering and technology, and to help them understand science concepts through engineering design. In this study, Lachapelle and Cunningham (2007) described their work with 5,139 students around the country who used the EiE curriculum, comparing results from pre- and post-assessments with a control sample of 1,827 students.

One of the units had students designing water filters, another had them designing hand pollinators. In the water filter curriculum, students learned about water pollutants and how to test for chemicals and particulates in water. Since students in the control group were only asked sample questions from each EiE unit, there was only one question on the assessment to compare between treatment and control groups. Control students performed significantly higher \( (p = .000) \) than EiE students on this particular question both in the pretest and the posttest. Pretest percentage correct for the control group was 77.3% and 46.7% for the experimental group. Posttest percentage correct for the control group was 84.9% and 59.5% for the experimental group. Researchers attribute this to the fact that treatment groups came from many states, whereas all control group students lived in Massachusetts and water is an important science concept taught at the fifth grade level. The EiE students, who took a 22-item test on science concepts, did however score significantly higher on 16 of the questions on the posttest than they did on the pre-test \( (p < .02) \). However, pre- and posttest percentage correct means were not reported on the assessment as a whole, but on individual items. When averaged together for the 22 items, the pre- percentage mean was 65.3% and the post- percentage mean was 76%.
In the hand pollinator unit, students learned about plants and insects and insects' role in plant reproduction. Students who participated in this unit were not compared to the control group because the control group was not shown to be representative of the experimental group. The control group contained a significantly higher percentage of minorities, English Language Learners, and students from low socioeconomic backgrounds. Additionally, the control group students were not necessarily taught the same science content as the experimental group. The EiE students improved significantly from pre- to posttest on 18 of the 19 questions \( (p < .001) \) of a 19 item assessment. Pre- and posttest percentage correct were not reported on the assessment as a whole, but on individual items. When averaged together for the 19 items, the pre- percentage mean was 56.1% and the post- percentage mean was 75.4%.

In this study, the results were strictly quantitative, and a detailed picture of exactly how these students learned science through manipulating the materials in the unit was not provided. The amount of time students spent on each design unit was also not reported.

Silk, Schunn, and Cary (2007) conducted a study that was a continuation of their ongoing work at the University of Pittsburg. In this study, they addressed the need for research on design-based science teaching and learning with students of low socioeconomic status (SES), and students in urban settings. Specifically, they sought to understand whether a design-based science curriculum would help this population of students perform on high-stakes standardized science assessments. The researchers implemented a 6-week design-based science unit called the Electrical Alarm System with
groups of eighth grade students in 2 teachers' classes at two urban public schools. One
teacher had 5 classes participate, and the other had 3 classes participate, for a total of 177
students with 170 participating. Sixty-three percent of participating students were from
low SES backgrounds, as determined by their qualifying for government-subsidized
lunch. As an informal comparison group, students in somewhat-similar schools engaged
in a guided inquiry-based curriculum on electricity. All students were given identical pre-
and posttests which contained eight questions on scientific reasoning. Two items were
from the Third International Mathematics and Science Study (TIMSS) (International
Association for the Evaluation of Educational Achievement, 1998), and six items were
from the Classroom Test of Scientific Reasoning (Lawson, 1978). The experimental
group was given five additional questions both on the pre- and posttest. Both instruments
were assessed for reliability. The eight-question instrument demonstrated low reliability
with a coefficient alpha of .49 on the pretest and .68 on the posttest. The 13-question
instrument had better reliability with a coefficient alpha of .57 on the pretest and .72 on
the posttest. The instrument was not provided with the paper.

The experimental group began the unit by discussing the various uses for alarm
systems, relating these uses to students' lives. The goal in this phase was to motivate
students by having them choose their own purpose for an alarm system and create their
own context for learning. Students worked in teams of 3 or 4 to choose a type of alarm to
design and build. Teachers assisted the groups when necessary, and like Hmelo et al.
(2000), tried to help students see the alarm as a system composed of subsystems that
worked together. The process was very open-ended, but students were provided with
some worksheets to help them stay focused on the tasks. Students were provided with a variety of electrical devices, including sensors, wires, batteries, bulbs, resistors, etc. Similar to the pin-up sessions promoted by Kolodner et al. (2003), teams were encouraged to share their work with the whole class several times during the unit, in order to receive feedback and improve on their designs.

Because the data on the students in the experimental group were not normally distributed, the researchers ran a paired means Wilcoxon signed-rank test to compare pre- and posttest scores. There was significant improvement in scientific reasoning ability ($p < .001$) with an effect size of .67. The pretests mean was .27 (out of 1.00) and the posttest mean was .39. While the effect size was large and the gain significant, these are still very low scores. The researchers then disaggregated the data into gender, ethnicity, socio-economic status (SES), and whether the student was in special education. They ran a multiple regression test on the data and found that gender and SES were not significant predictors of achievement; but that the students in special-education did not perform as well as regular education students and that the minority students did not do as well as Caucasian students. The researchers postulated that this difference for minority and special-education students might have been due to reading abilities. They tested this hypothesis with an additional regression analysis including scores from a previously-taken standardized reading test, and found that lower reading scores were a predictor for poor performance on the posttest. Even still, the highest mean score in any subgroup was .52, the score on the posttest by the Caucasian subgroup.

The final analysis the researchers conducted was to find out whether students in
the design-based science curriculum learned more science reasoning skills than students in traditional curricula. The traditional curriculum was Model Assisted Reasoning in Science (MARS). The MARS assessment shared six items with the 13-item assessment used in the design study. On these six items, students in the MARS curriculum did significantly better on the posttest than students in the design-based science curriculum ($p < .001$). The posttest mean for students in the MARS curriculum was .43 (out of 1.00) compared to .34 in the design-based curriculum. However, the MARS curriculum is a 3-year inquiry-based curriculum that focuses on bridging the abstract with concrete science. Students in the control group had been learning science through this curriculum since sixth grade, which gave them an advantage over a 6-week design-based course. The researchers predicted that if students worked with design-based science curricula for that many years, it would possibly have a greater impact. Also, some of the schools in the control group were much less diverse, with only 8% of control-group students having a low SES background.

In order to compare design-group students to students in a traditional textbook-based curriculum, the researchers used data from a study that compared students in the 3-year inquiry-based MARS curriculum to students in a traditional textbook-based curriculum (Zimmerman, Raghavan, & Satoris, 2003). They concluded that the 170 students in the design-based science curriculum significantly outperformed the 269 students in the textbook curriculum ($p < .001$) on the six items common to both assessments. It was reported that students in the textbook curriculum scored .21 (out of 1.00) on the posttest compared to students in the design-based curriculum who scored .34
on the posttest. This indicates that the 6-week design-based curriculum is superior to a traditional textbook curriculum, at least in terms of students answering six questions on a multiple choice assessment. The authors are currently working on an electricity comprehension test and plan to use it with future research on the alarm system design unit (E.M. Silk, personal communication, May 12, 2007).

The University of Pittsburg group continued their work with students designing alarm systems and in 2008 published their latest results. Mehalik, Doppelt, and Schuun (2008) worked with a much larger sample implementing their unit. The experimental group consisted of 10 teachers and 587 eighth grade students designing alarm systems, while the control group consisted of 5 teachers and 466 eighth grade students learning electricity through guided inquiry. Each unit took 4-5 weeks. The teachers in the experimental group selected this approach as part of their professional development, and were compensated for participating in the research. The teachers in the control group were not compensated. Students in the design group were more likely to come from low socioeconomic backgrounds (53% versus 32%). Identical seven-item pre- and posttests on electricity concepts were administered to both groups. Neither validity nor reliability information about the researcher constructed instrument was provided, although the multiple-choice instrument was provided in the paper. Students in the experimental group made a 16% gain from pre- to posttest while students in the control group made a 7% gain from pre- to posttest. This difference was significant ($t = 2.02; p < .01$) with an effect size of .89. Both groups achieved statistically similar scores on the posttest: the experimental group scored .45 (out of 1.00) and the control group scored .46, but their
pretest scores were very different: the experimental group scored .29 for and the design group scored .38. As with the previous study which used this electricity focused design curriculum (Silk, Schunn, & Cary, 2007), the test scores were very low. Perhaps this is an issue of test design. The fact that neither reliability nor validity information about the electricity test was included in the paper makes it suspect. Paired *t*-tests could have provided more information. The researchers concluded that the design-based science curriculum did a better job at reaching students of lower SES. Since the research report did not include a qualitative analysis, it is difficult to compare the treatments and understand how classroom interactions played out. The classrooms were only visited by a researcher on average of three times over a 4 to 5 week period, and some classes were not visited at all.

Research on the Design of Models

As an alternative to having students design, build, and test unique artifacts that solve problems, students can design, build and test models of complex structures. The following three studies have students building models of human anatomy in order to more fully understand the scientific principles that allow the anatomy to function. These three studies represent the only ones in this literature review that have students working in the life sciences. Perhaps building models of human anatomy is a good way to integrate design-based science into the life sciences.

Penner, Giles, Lehrer, and Schauble (1997) of the University of Wisconsin utilized a design activity to teach first and second grade students about how scientific
models can be used to simulate function. Their rationale for the study was based on research that showed that children view science as a discipline focused on accurate observations, and that children do not see the role for building and testing models in order to construct and test theories. The researchers chose design as a context for helping children develop an understanding and appreciation of model construction and revision.

School children are primarily familiar with models that represent form, not function. Models can simulate either, and different functional models can be used to explain the same phenomenon, serving as rival theories. The researchers sought to understand how 48 first and second grade children’s notions of models evolved over the course of the three 1-hour model-building activities. Students worked in pre-selected pairs or triads with a standard bin of materials with which they were to construct a model of the human elbow. After the first iteration of model building, the teacher led a discussion with the students about how their models simulated the function of the elbow. A second model-building iteration allowed students to modify their models or start over again. After the lessons were completed, 19 children representing a range of ability levels were interviewed by the researchers. A control group of 13 second grade and 9 fourth and fifth grade students were interviewed as well. Analysis of interviews and classroom activities suggested that children as young as first grade were capable of understanding the functional purpose of models. Children who participated in the modeling activities understood the modeling process as well as the older children in the control group who were interviewed. However, participants did not learn implicitly from these activities that models could be used to explain scientific principles. This study demonstrated that
design-based science could be used to teach students about summarizing patterns in data, although in this case, the design activity was used only to assess young children’s capacity to learn about the function of models, not the underlying scientific principles of leverage. While Roth (1996) used design to teach about engineering and mechanics yet did not directly address or assess understandings of the science of mechanics, Penner et al. (1997) directed a study in which students learned about how models are used in science, but they did not directly address or assess understandings about how models serve to tell us something about the underlying scientific principles at work.

A year later, Penner, Lehrer, and Schauble (1998) published a continuation of their studies of how children can design models in an attempt to understand the natural world. This time, the researchers worked with a group of 17 third grade children. Once again, children were instructed to build models of elbows from a kit of materials. Children worked in pairs or triads, proceeded through two iterations of design, and spent four 45 to 60 minute class periods on the activity. However, in this study, the researchers added an activity after the design phase. They had students experiment with levers, trying to link the design activity to the science concept of leverage, and to the concepts of how different bodily joints move. The data they collected was through field notes, audio recordings, and student work. Students constructed a graph with the teacher’s help, and were asked to interpret meaning from the graph. The graph illustrated that more force is needed to move a fixed mass when the mass is at a greater distance from the fulcrum. The students had difficulty creating a general principle that would explain the graph. Even after the teacher used a familiar analogy (a playground teeter-totter), and analogies of
different bodily joints to compare the lever to, students still did not understand the physical principles at work. They could describe patterns, but they could not explain the principles behind those patterns. The researchers concluded that more work needs to be done to help students understand the principles of leverage that create motion in our joints, but they did not post how that work should be accomplished. They did not come to the conclusion that if students were allowed to think outside of the proverbial box of materials they were given, and brainstorm what else they might have needed in order to build a functioning model of a human elbow, perhaps they would have requested some anatomy diagrams, or even some chicken wings from the grocery store to see how muscles and tendons attach to bone. While it is true that designers have to learn to work within constraints, information should not be constrained if learners so desire it.

Hmelo, Holton, and Kolodner (2000) investigated two classes of sixth grade students as they were learning about their respiratory systems through the two and a half week unit on the design and modeling of human lungs. In this study, the authors referred to the Penner et al. (1997, 1998) studies of children modeling the human elbow, and stated that their study built on those studies by encouraging the sixth-graders to view complex systems as designs. They hoped to encourage students to move beyond definitions and functions, and truly understand how systems behaved. Specifically in this case, the system to be understood was the relationship between structure and function in the human respiratory system. Unlike in the Penner et al. (1997, 1998) studies, students were introduced to a collection of resources: books, drawings, and multimedia software, to help them understand the scientific concepts they need to know in order to build their
models. They were provided with an assortment of materials, and allowed to bring in materials from home as well, such as clay and a motorized construction set. One student even suggested dissecting a mammal to see how the lungs work. This was one of the first studies done with the then newly-developed Learning by Design™ approach spearheaded by Janet Kolodner at the Georgia Institute of Technology (Kolodner, Crismond, Gray, Holbrook, & Puntambekar, 1998). Working from a PBL model, and incorporating case-based reasoning (Eshach & Bitterman, 2003), the authors created a design task for middle school students that would engage and challenge them, enable them to connect to the real world, and encourage reflection. Students worked in groups of 3 or 4 for the entirety of the project. While reflection might be periodically facilitated by a teacher with the whole class, the primary interactions were between students and their whiteboards in small groups.

The students were told to monitor their thinking processes by keeping up with a whiteboard with columns for facts, ideas, learning issues, and action plans. It served as an anchor to help students see where they had been and focus on where they were going with the design. It also served as a tool for the teacher or group facilitator to check on students' thinking and scaffold their ideas where necessary.

All classroom activities were observed and videotaped on a daily basis, and field notes were taken to capture descriptions of the activities and environment. A third classroom served as a control. Students in the control class learned about respiration through lecture, discussion, and textbook readings. It is unclear whether the control classroom was taught by the same teacher. All students in the study, both those in the
experimental classrooms \((n = 42)\) and the control classroom took a 12-item true-false pre- and posttest on the science of the respiratory system.

As in the Penner et al. (1997, 1998) studies, students initially built their models based on form, not function. After initial attempts, many of them moved on to build more functional models. Students in this study had many outside resources available to them: they had the whiteboard structure to keep them focused on their questions and goals and provide an "external memory", and they had two and one half weeks devoted to the project.

All students were administered a 12 question true-false pre- and posttest. Validity and reliability data were not provided about the instrument. Students in the experimental classes increased their scores from pre- to posttest, \(F(1,32) = 6.23, p < .05\) whereas students in the control class did not, \(F(1,12) = 1.76, p > .15\). The actual mean scores were not reported, nor were the effect sizes. On a bar graph on page 279 depicting the percentage correct on pre- and posttests for both treatment groups, one must look closely to notice a slight difference between the two groups, which hovered around 75% correct both pre- and posttest.

Students were also asked to draw their conception of the respiratory system both pre- and post-instruction. Researchers developed a coding scheme to analyze these drawings, and results indicated that students in the design group had the more sophisticated mental models of the respiratory system after instruction \((p < .005)\) than students in the control group \((p > .25)\). The experimental group had 4 students out of 18
pre-instruction with sophisticated models and 5 students post-instruction. The control group had 3 students out of 13 pre-instruction with sophisticated models and 1 student post-instruction.

Pre- and post-instruction interviews were conducted with both groups, but technical difficulties made listening to the control group's post-interviews impossible. The interviews were coded for student understandings, but the coding scheme was not described. Students in the design groups displayed a statistically significant increase in coherent understanding of the respiratory system after instruction, $F(1,17) = 6.16, p < .05$ but the difference in numerical codes pre and post is difficult to interpret. For example, for the code of knowledge of structures, the pre-instruction interview code mean was 7.00 and the post-instruction code mean was 7.61. For the code of knowledge of connections between structures, the pre-instruction interview code mean was 0.33 and the post-instruction code mean was 1.17. For the code of knowledge of causal behaviors, the pre-instruction interview code mean was 0.94 and the post-instruction code mean was 1.80. Without a range in which to situate these codes, they are difficult to interpret.

Researchers reported that the students in the design group did not have enough time to complete their models and that each group only had a partially working model complete at the end of the study. Researchers concluded that if students had been given more time at the beginning of the design challenge to generate tentative models, and given more time at the end of the study to reflect on and modify their models, that they could have learned even more. Additionally, the researchers did not think that the teacher provided enough scaffolding in the areas of design, debugging the design, or explaining
the designs to the class. This study represents one of the better experimental designs in this review. The researchers included qualitative data in the form of conversation excerpts, vignettes and drawings, a control group of similar students learning the same science content in a traditional manner, and the statistical analyses of various pre- and posttest assessments of science knowledge, although much information about how the students scored on these assessments was not provided. Science content knowledge was assessed three ways: through a true/false test, a drawing of the respiratory system, and interviews with students in the experimental group.

Research on Virtual Designs

With the evolving role of computer simulations for teaching and learning science classrooms, it was no surprise when researchers began comparing students designing physical artifacts to students designing virtual ones with computer simulations. The following two studies have students designing structures and vehicles through computer simulations, and results are inconclusive as to whether computer design simulations are as effective as physical design and construction activities.

Klahr, Triona, and Williams (2007) studied 56 seventh and eighth grade students who were given the challenge to build a mousetrap-powered car that could travel the greatest distance. While one group of students was randomly assigned to work with actual materials in a kit that included wooden frames, string, wheels, and mousetrap motors, another group built model mousetrap cars on the computer with software that allowed them to test their designs. The time allowed for the design activity was not
clearly delineated in the paper. Both groups were tested pre- and post-instruction on their knowledge about how different features of the car such as body length or axle width affected its performance. Neither validity nor reliability data were provided about this knowledge assessment. The number of mousetrap cars they could build and test was also computed and compared. Children in the virtual group built an average of 20.1 cars each compared to children in the physical group who built an average of 6.1 cars each. This difference was significant at $p < .0001$. The knowledge assessment consisted of six multiple choice questions. The mean for all children pre-instruction was 2.5 out of 6 points, significantly better than the “random guessing” score of 2 points ($p = 0.01$). The mean score for all children posttest was 4.0. Both groups made knowledge gains that were significant, $F(1,52) = 121, p < .0001$, but differences between the groups were not significant. These means were not reported but it can be inferred from a bar graph that the means for both groups hovered around 4 points. Both groups learned equally well. The assessment, which was included in the paper as an appendix, consisted of questions related to design choices, not scientific concepts. Finally, the researchers compared the performance of the virtual cars. The mean distance travelled by cars in the virtual group increased from their first design to their last design. The mean pretest distance was 24.4 feet and the mean posttest distance was 38.6 feet, significant at $p < .0001$. This difference was not reported for students in the physical group.

The researchers used these results to question the National Science Teachers' Association (NSTA) position statement that students should engage in “hands-on” activities, and that computers should not replace these “hands-on” experiences (NSTA,
They touted the benefits of virtual design, stating that it took less time, saved money, and allowed the students to build more "cars".

Svarovsky and Shaffer (2007) also centered on students’ ability to learn design through computer applications. Svarovsky and Shaffer also cited the cost and time factors built into hands-on designing and constructing of artifacts, and stated that engineers use virtual computer environments for design in the early phases of product development. Svarovsky and Shaffer worked with 12 middle school students during a weekend workshop while they used a computer simulation to build structures. The workshop lasted 10 hours, 5 hours each day. Six students were in each workshop group, working in self-selected teams of 2 or 3 students. The students volunteered to be in this workshop, and there were 10 males and 2 females. They used a Java-based modeling system called SodaConstructor that let them create structures and test them against simulated gravitational forces. Students were given design challenges of increasing complexity. The first challenge was simply to build a standing structure. The final challenge was to build a cantilever. Students worked individually at computers then discussed their designs with each other and chose the best design per team to display in a virtual poster session.

Students were interviewed both prior to and after the weekend workshop. The interview protocol involved both general and scientific questions. These interviews were transcribed and analyzed using coding categories that developed from trends and patterns. Only two codes of the ten related to a single scientific concept - center of mass. The

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1 This free online Java applet can be found at http://sodaplay.com/creators/soda/items/constructor
number of times a student referred to the center of mass was tallied, and paired \( t \)-tests were run to compare the number of references to center of mass pre-interview and post-interview. Students' references to and understandings of the center of mass increased significantly, with \( p < .01 \). While means or ranges of means were not reported, the mean difference was reported as 11.5 points, which has no importance without context.

The researchers acknowledged limitations to this study, such as students' prior interests in science or engineering, since they chose to participate in this weekend workshop. They did not acknowledge the lack of a control group, small sample size, or the gender imbalance. Additionally, the only science concept assessed was center of mass, which seems insufficient considering the fact that 10 hours were spent on the activities.

Conceptual Change

Prior to reviewing studies which have explicated students' alternative conceptions of heat and temperature, it is important to briefly describe the field of research called conceptual change.

Because students come to school with deeply rooted beliefs, or alternative conceptions, about how the world works, these beliefs can commonly contrast with current scientific views. Research into the conceptions about scientific phenomena that students develop has been an important focus of science education for over 3 decades (Duit & Treagust, 2003).

Initially, these conceptions held by children were termed, "misconceptions", a
term some regard as negative, implying that the child holds mistaken ideas that only need to be corrected. More recently, the terms, “naïve conceptions”, “pre-scientific conceptions”, “alternative frameworks”, or “alternative conceptions” have come into popular use (Wandersee, Mintzes, & Novak, 1994). The conceptions that children develop are creative and useful to the child as he or she navigates the practical world, and thus must be respected as such (Brown, 1992; Clement, 1993), but teachers must focus on helping students restructure their current knowledge.

These alternative conceptions are resistant to change and people of all ages are usually very reluctant to discard their long-held beliefs. They need to come to a point where they are dissatisfied enough with their initial conception to adopt a new, more scientific one. By identifying these conceptions and understanding some of the reasons why they are so persistent, teachers can begin to address them appropriately. 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 remediate alternative conceptions is through concrete, understandable, believable, explicit, and visual examples. Students need to experience these examples, not simply be told them (Brown, 1992). Another effective method is through the use of bridging analogies that are easy for a student to understand. For example, a student may understand that a trampoline puts a force on a person when the person is not moving. The student can understand that the person puts a force on the trampoline and it deforms. This analogy can be used to help students understand that a
rigid table puts a force on a book place upon it, even though the table does not appear to flex. Experimental lessons and demonstrations can also serve as bridging analogies (Clement, 1993).

Entire books have been written about the detailed alternative conceptions students possess about nearly every facet of science (Driver, Guesne, & Tiberghien, 1985; Driver, Squires, Rushworth, & Wood-Robinson, 1994), and the literature is rich with descriptions of students’ alternative conceptions of heat and temperature. However, none of the studies on design-based science that were reviewed earlier contained any references to students’ alternative conceptions. The work only begins with identifying students’ alternative conceptions; the next step is to help students restructure their knowledge so that it fits scientifically accepted conceptions. This work is done through the conceptual change model.

*The Conceptual Change Model*

The conceptual change model informs educators about how to best address students’ alternative conceptions in science. The first conceptual change model to be proposed was by Posner, Strike, Hewson, and Gertzog (1982), although the conceptual change model has been revised over the past 2 decades by Hewson and Hewson (1983) and others. Posner et al. (1982) posit that the learner must first be dissatisfied with existing conceptions in order to discard or modify them. The new conception presented must be intelligible to the learner, and analogies or metaphors can help new conceptions make logical sense. 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. Hewson and Hewson (1983) describe these three conditions of a new conception as intelligible, plausible, and fruitful, and state that teaching strategies can follow once these three conditions have been met. They speculate that the first phase of conceptual change is integration, as new concepts are integrated with existing ones. This is followed by differentiation, as existing conceptions are defined and shown to be separate from more scientific ones. What follows is an exchange of old conceptions for new ones as students see that old conceptions are not plausible and new conceptions are more explanatory. Finally, the student can link the new conceptions with their experiences.

Children’s Conceptions of Heat and Temperature

As children are swaddled and bathed, they are exposed to and shielded from the effects of heat and temperature from birth. Their conceptions of what defines “hot” and “cold” form quite young (Erickson, 1985). In this section, five studies designed to determine students’ alternative conceptions of heat and temperature will be summarized, and students’ alternative conceptions will be described.

Albert (1978) interviewed 40 young children ranging in age from 4 to 9 years. She asked these children a series of questions such as “Give me examples of heat” or “Give me examples of warm.” She found that at 2 years of age, children learn which objects feel warm and which ones feel cold, and that by age 4 to 6, children can identify what makes them feel hot or warm, that the sun makes it hot outside, and that switching on household appliances (lights, ovens, televisions) makes them hot. By the age of 7 or 8, children begin to conceive of heat and the directional nature of heat, and soon thereafter
reflect on how heat affects their bodies, i.e., it makes them hot. By the age of 10, children understand the notion that there are different levels of heat, and begin describing temperature in terms of degrees on a scale. They also understand that the activity of a machine, physical object, or person, produces heat—the nascent conceptualization of mechanical energy as a source of heat.

Erickson (1979) interviewed ten 12-year-old children about their conceptions of heat and temperature. Demonstrations were used to elicit children's explanations and a conceptual inventory was generated for each child to represent their own particular pattern of beliefs. Themes common to all 10 children were compiled to create a composite of what alternative conceptions 12-year-old children might typically hold about heat and temperature:

1) heat is something that rises
2) cold is a substance that moves
3) heat moves through a substance because it builds up at one part and breaks free
4) heat is like a fluid that flows
5) air has to get inside something to make it hot
6) soft things melt easier than hard things
7) larger ice cubes are colder than smaller ice cubes
8) heat is a substance
9) temperature is a measure of the mixture of heat and cold
10) all objects contain a mixture of heat and cold
Erickson went on to recommend 17 different classroom activities that might ameliorate the teaching and learning of scientifically correct conceptions of heat and temperature. These activities involved a) measuring the temperature of classroom objects and objects in three states of matter, and different quantities of the same substance, b) observing anomalies such as measuring the temperature change of water when different types of objects at the same temperature are added, observing different quantities of water being heated, placing hot objects on a block of wax to see how they behave differently, and c) discussing activities as a class or in groups, discussing the anomalies, and exploring possible explanations.

Erickson (1980) continued his research with children with the goal of creating a more generalizable set of their ideas about heat and temperature. He worked with 76 fifth grade students, 117 seventh grade students, and 83 ninth grade students, developing an instrument called the Conceptual Profile Inventory (CPI) to determine whether they held alternative conceptions typical of children, viewpoints aligned with the discarded caloric theory of heat (that heat is a fluid made of heat particles), or the current kinetic energy viewpoint. While validity was not reported on this instrument, reliability was assessed with Hoyt reliability coefficients for each question, and these reliability coefficients ranged from .85 to .92. Students were shown demonstrations and asked to choose the explanatory theory they preferred. One such demonstration was of aluminum rods of different thicknesses being heated. Another involved heating same-sized small cubes of different materials and then placing the cubes on a surface of wax to see how far they sank into the wax. A third demonstration involved measuring the temperature of water
prior to and after an ice cube was placed in it. The final demonstration involved an Erlenmeyer flask filled with red liquid, sealed with a one-hole stopper with a capillary tube sticking up through it. Erickson placed the device into a bath of hot water and students observed the red fluid rising up through the capillary tube. Erickson found that as students tried to explain these four demonstrations, alternative conceptions typical for 12-year-olds were prevalent in both the younger and older age group, and that the caloric theory was prevalent at all three grade levels as well. For example, in the first demonstration, students thought that the larger aluminum rod attracted more heat particles than the smaller rod, and that the larger rod had more air spaces for heat to travel through, ideas consistent with the incorrect and outdated caloric theory of heat. They thought that heat built up in one part of the rod until the rod could not hold the heat any longer, and that heat particles from the flame were attracted to the rod. In the second demonstration, students thought that the heat particles in the cubes went inside the wax and forced the wax particles apart and that the metal cubes drew in more heat particles than the other cubes. For the third demonstration, students thought that the larger ice cube was colder than the smaller one, and that cold from the ice cube went into the water. In the final demonstration, students thought that heat made the red liquid lighter, so it rose. They also thought that heat particles were taking up space, pushing the red liquid up the tube. Erickson analyzed the frequency of these opinions and found that the caloric theory was more prevalent than other theories at all three grade levels.

Clough and Driver (1985) interviewed 84 students aged 12 to 16 from three urban schools about their conceptions of heat and temperature. The students were purposefully
selected to represent a range of ability levels. The purpose of the study was to identify common beliefs the students had about heat and temperature across age levels and abilities. The researchers presented students with a variety of situations and asked them to comment on them. The first situation was of four spoons of different materials in a mug of hot water. Students were asked to feel the handles and explain why some felt hotter than others. The next situation involved two plates of different materials that had been in the room overnight. Students were asked to predict the temperature of these two plates and explain why one felt colder than the other. The final situation was a thought experiment. Students were told to imagine a bicycle outside on a frosty day, and explain why the metal handlebars might feel colder than the plastic grips at the ends.

Clough and Driver found that “many of the notions used by younger children are still apparent in the thinking of older students” (p.176). They still thought that metal was naturally colder than plastic, that heat rises, that metal attracts and absorbs coldness, that metals pull heat toward them like a magnet, and that soft objects are warmer than hard ones. The researchers posited that these older students may have been able to demonstrate an understanding of heat and temperature on school paper and pencil assessments through their familiarity with scientific-sounding phrases, but that when students were asked to apply their ideas in novel contexts, the holes in their conceptual understanding became apparent.

Paik, Cho, and Go (2007) interviewed 154 students in South Korea, aged 4 to 11. The children were selected by their teachers for the interviews, and were specifically chosen because they represented average achievement. Interviews consisted of seven
questions about temperature, thermal insulation, and heat equilibrium. The researchers probed for students' reasoning behind their answers. They compared the interview responses across participant age.

Between 20% and 55% of all 9, 10 and 11 year olds stated that a larger ice cube would be colder than a smaller one. The most common rationale in older students was based on the time-to-freeze. If the larger cube took longer to freeze, they rationalized; it must contain more "coldness." Approximately 60% of 9, 10, and 11 year olds predicted that two cups of water with different temperatures would have an intermediate temperature when combined. The rest of the students predicted a final temperature above the higher temperature or below the lower temperature. Between 70% and 85% of all 9, 10, and 11 year olds predicted that aluminum foil would be better than thick cloth or any other material to keep an ice cube from melting. The most common rationale was that aluminum foil was perceived to be intrinsically cold, and cloth was perceived to be an intrinsically warm substance. Students also stated that since aluminum foil is shiny, it must reflect light and therefore, heat. When asked what container material be used to keep warm water warm longer, between 60% and 75% of 9, 10, and 11 year old students predicted that metal would be the best material, while a much smaller percent predicted that Styrofoam would be the better choice. Students stated that since Thermos bottles are made of metal, and since metal is intrinsically a warm substance; it would be best to keep warm water warm longer. Students were also asked about heat equilibrium, and most 9, 10, and 11 year old students reasoned that if hot water were put into a metal container, the container would have a higher temperature than the water because the metal was
perceived to absorb heat fast. When asked whether a piece of metal or a piece of wood would be warmer when placed in warm water, over 80% of students aged 9, 10, and 11 predicted that the metal would be hotter. The most interesting finding from this research on students’ conceptions about heat and temperature was that in many cases, 4-year olds answered the questions correctly more often than the older students. Researchers concluded that many misconceptions held by the older students were formed in science classes at school.

The following section describes instructional interventions in the content area of heat and temperature that purport to adhere to the conceptual change model.

Instructional Interventions about Heat and Temperature

While the literature is rich with descriptions of children’s conceptions of heat and temperature, it is sparse in terms of interventions designed to help children work through those conceptions and reach more scientific ones. The following four reviews include interventions that used computer simulations, concept maps, examples and demonstrations, and card sorting activities to help students learn concepts about heat and temperature. No rigorous studies could be found to help students learn heat and temperature through design-based science.

Clark and Jorde (2004) conducted a study in which a five class period intervention took place on thermal equilibrium. The researchers discovered that helping students understand thermal equilibrium (the concept that objects at the same temperature may feel different) helped them understand other concepts related to heat. Students used a
computer simulation to predict and test the temperature of different materials. They also predicted and tested the temperature of objects around the classroom with temperature probes. Four classes of standard-level eighth graders participated, totaling 120 students. Sixty students were in the experimental group and 60 were in the control group. Both groups used the simulation, but the software that the experimental group used had an additional feature. When the student would click on an object with the mouse, the computer would say and display, “that feels hot” or “that feels cold.” Students were given pretests, posttests, and delayed posttests on thermal equilibrium. These content tests contained 10 items; four on thermal equilibrium and five on general thermodynamics principles learned earlier in the unit on heat and temperature. For the four questions on thermal equilibrium, a Cronbach’s reliability coefficient of .395 was measured on the pretest, .895 on the posttest, and .925 on the delayed posttest. Measures of validity were not reported. Delayed posttests occurred 6 weeks after the intervention. Analysis of Variance (ANOVA) was used to compare students’ performance on these tests. Students in the experimental group performed significantly better on the four thermal equilibrium questions and on the five general thermodynamics questions on the posttest and delayed posttest than students in the control group, however means were not reported. On the first question about why objects feel hot or cold, students in the experimental group performed significantly better than control group students ($F (1, 100) = 26.1, p < .0001$). Means were not reported, but it can be inferred from the bar chart that approximately 73% of students in the experimental group correctly answered this question on the posttest whereas only approximately 28% of students in the control group did. On the next four
questions related to thermal equilibrium, students in the experimental group performed significantly better than control group students \( (F (1, 100) = 7.7, p = .007) \). Means were not reported, but it can be inferred from the bar chart that approximately 87% of students in the experimental group correctly answered these questions compared to 61% of students in the control group. Students in the experimental group also performed better on the questions not related to the intervention on thermal equilibrium. Neither means nor statistical measures were reported to support this claim, however the researchers hypothesized that helping students understand thermal equilibrium helped them with general thermodynamics concepts as well.

Students who scored in the middle third of the class on their pretests were interviewed both after the pretests and after the posttests. They were also videotaped during the intervention, but an explanation for this was not provided. Interviews consisted of six questions and were designed to give the researchers insight into how the computer simulation affected students' understanding of thermal equilibrium. Students reported that they liked the simulation because they could see arrows which represented heat flowing into or out of a material. Researchers reported that the computer simulation was successful in targeting resistant alternative conceptions on thermal equilibrium.

Lewis and Linn (1994) conducted a two-phase study in which they elicited conceptions about heat from a variety of participants, and then conducted an instructional intervention which was shown to help students with scientific conceptions of heat. The researchers found that alternative conceptions about heat are present in both students and non-scientist adults alike. In the first phase of the study, 32 eighth grade students, 9 non-
scientists adults, and 8 physical scientists were interviewed about their conceptions of thermal events. The participants were asked a variety of open-ended questions and their responses were either audio or video taped. The adolescents and non-scientist adults were told that the purpose of the interview was to learn how people think, and that there were no correct or incorrect answers. The scientists were told that the purpose of the interview was to elicit their help in planning ways to teach thermodynamics to middle school students. The eighth graders were also tested on their conceptions of heat energy, temperature, thermal equilibrium, and heating and cooling. The items were designed to address common alternative conceptions about thermodynamics. Intuitive conceptions (alternative conceptions) were identified from the interviews and tests, and found to be consistent for adolescents and non-scientist adults. These alternative conceptions were that metals attracts and hold “cold” so that metals are good insulators for cold things, that insulators do not trap heat and thus conduct heat away, and that wool warms things so that it cannot be an insulator for cold things. Some of the scientists gave interview responses that reflected undeveloped understandings of heat and temperature.

The second phase of the study involved an 11-week curriculum intervention with 151 eighth grade students called CLP (Computer as Lab Partner). The teacher improved upon the CLP curriculum by including instructional components based on the research results from phase 1 of the study. The teacher began with a series of well-planned demonstrations and student-conducted experiments designed to elicit students’ alternative conceptions. Identical pre- and posttests were administered to the students in the CLP program. These tests had been developed by the researchers over time, and while
reliability and validity evidence was not provided about this instrument in this particular paper, reliability was purportedly reported in other publications by the authors. However a check of those publications yielded only that a test-retest procedure was used to establish reliability without a description of the results of that procedure.

Pretest means were 2.0 out of a possible 9 points. Posttest means were 6.6 out of a possible of 9 points, which represented a statistically significant difference ($p = .0001$). The CLP curriculum was not described in great detail, but it did involve different simulations of experiments that students would conduct on the computer with heating and cooling objects. Eleven weeks is a very long time to have students focus on one science topic in school. This study was completed in 1994, and today it seems unrealistic for a teacher to spend nearly 3 months of the school year on one topic. It is not surprising that students did well on a 9-point test after 11 weeks of instruction. There was not a control group to which to compare the students using the intervention, so it is not convincing that this particular intervention was any better than standard instruction for 11 weeks on the topic of heat and temperature.

Jones, Carter, and Rua (2000) studied 61 fifth graders in five different classes as they worked in pairs for 3 days on activities related to convection. Fifteen student pairs were interviewed before and after the intervention, which was led by the researchers. The intervention involved students observing convection currents in water and air, and answering questions on paper about the similarities and differences they observed. Students drew concept maps about their knowledge of heat prior to the intervention, reviewed the concept maps after the intervention, and created new concept maps.
Students also participated in a card sorting activity after the intervention, and both the card sorting and the concept map were topics of conversation in the post interviews. Students often used familiar analogies in their interviews to help them explain convection. They relied upon prior experiences to explain their knowledge on paper in the concept maps and during the card sort. Discourse analysis during class provided information about students' prior knowledge and how new observations were interpreted. For example, students were provided with the example of a dense forest located next to a city. They were asked to predict how air would move. Some students thought that the air would move into the forest because the forest needed more moisture and oxygen. Other students thought that the air would move into the forest because the automobiles creating heat from friction. The researchers concluded that the different types of assessments drew on different “communities of concepts that exist within students’ conceptual ecology” (p. 155). They also concluded that proper sequencing of instruction is important for students to make sense of each new concept. They concluded that the cultural experiences of the students are an important source of analogies and examples, and that the diversity of students’ backgrounds will be reflected in the ease with which they respond to instruction.

Rogan (1988) studied 145 ninth grade students in four classes as they participated in lessons about heat. They were exposed to two theories of heat: two classes were taught both the kinetic theory and the caloric theory (the conceptual change groups), and two classes were taught only the kinetic theory (the single theory groups). Additionally, two classes had students working individually while two other classes had students working
in pairs. This resulted in a 2 x 2 factorial design. Students learning both theories were challenged to choose which theory best fit the data.

Students were given a scientific reasoning test prior to the intervention in order to be classified as either high reasoners or low reasoners. This level of reasoning was used in the analysis of subsequent data. Conceptions of heat transfer were measured with the 29-item Conceptual Profile Inventory (CPI) developed by Erickson (1980) as a pretest, posttest, and retention test with 4 weeks separating each test. Three test items were discarded prior to administration because they were shown to be unreliable. Six items were discarded after the administration because they were shown not to target a particular theory (kinetic, caloric, or other) resulting in a 20-item evaluation with reliabilities measured for each item with the Hoyt reliability coefficient ranging from .88 to .92. Information about validity was not provided. The CPI was designed to determine if students possessed a kinetic, caloric, or other theory of heat.

A repeated measures ANOVA was used to analyze the data and determine whether students discarded the caloric theory in favor of the kinetic theory of heat. Initially, the caloric theory and other theories dominated the students’ conceptions. All groups increased in their ability to identify with the kinetic theory of heat but when students worked individually instead of in collaborative pairs, they made statistically greater gains in discarding the caloric theory regardless of whether they were in the conceptual change group or the single theory group \(F = 2.43, p < 0.1\). For example, on a scale from -3 to +3 with +3 representing high allegiance to a theory and -3 representing low allegiance to a theory, students with high reasoning skills working individually in the
conceptual change groups scored a mean of 1.11 on allegiance to the caloric theory pretest, 0.29 posttest, and 0.16 delayed posttest. Students with low reasoning skills in the conceptual change groups scored a mean of 0.85 pretest, 0.33 posttest, and -0.07 delayed posttest. Students with high reasoning skills in the single theory groups scored a mean of 1.18 on the pretest, 0.14 posttest, and 0.00 delayed posttest. Students who tested to be high-reasoners made statistically greater gains in discarding the caloric theory ($F = 11.91, p < .01$). High reasoners had an easier time discarding the caloric theory when they were in the kinetic theory-only groups while low reasoners had a more difficult time discarding the caloric theory when they were presented with both theories and had to determine which one better fit the data. For example, students with high reasoning skills in the single theory/cooperative learning groups scored a mean of 1.03 on the pretest, 0.25 on the posttest, and 0.36 on the delayed posttest. Students with low reasoning skills in the conceptual change/cooperative learning group scored a 1.28 on the pretest, 1.29 on the posttest, and 0.92 on the delayed posttest. It was better for both low and high reasoners to be presented with both theories, as it facilitated conceptual change. The researchers concluded that it is preferable for teachers to present alternative conceptions to students, as this promotes conceptual change.

Summary of the Literature

The following section includes a summary of the studies that addressed design-based science, the studies that elicited alternative conceptions about heat, and studies that used interventions to help remediate students' conceptions about heat.
Summary of Design-Based Science

Through analyzing these 16 design-based science studies that represent a span of more than a decade of research it can easily be recognized that the work is certainly not finished. There are still many unanswered questions. What we do know is that students can successfully engage in design-based science at any age and in any discipline. However, students engaged in design activities do not automatically learn science. Design-based science curricula need to be carefully designed so that students take away more from them than just model cars or boats (McRobbie et al., 2000). Design-based science curricula can take the form of model construction, and this can indeed help students understand the underlying scientific principles of nature if it is explicitly taught, and if students are given the intellectual freedom to explore the mechanisms built into the scientific processes they are modeling (Hmelo et al., 2000; Penner et al., 1997, 1998).

Design in the science classroom ought to be set into a context of interest to students, and tap into students' own intellectual curiosity. When design challenges are forced on students in a constrained manner, students may lack enthusiasm for the tasks. Ownership is an important component of design in science (Fortus et al., 2004; Seiler et al., 2001). Science learning should occur naturally as teachers assist students, and as students realize what they need to know and pursue it (Fortus et al., 2004; Mamlok et al., 2001; Puntambekar & Kolodner, 2005). The teachers assisting the students may have a significant effect on how students learn science through design. Teachers who are not as familiar with the theoretical framework of social constructivism, or who are not comfortable teaching in a style more appropriately called coaching, may not be as
successful as they wish to be (Mamlok et al., 2001). Teachers do well when they make use of certain tools and strategies such as design diaries (Puntambekar & Kolodner, 2005), guided worksheets (Silk et al., 2007), whiteboards, and pin-up sessions (Hmelo et al., 2000; Kolodner et al., 2003). Students who learn science through design may be better prepared to transfer their knowledge and skills to new situations than students who learn science through traditional methods (Kolodner et al., 2003). Finally, computers can be used as tools in design, not only in the early stages of the design process, but for research, and for rapid construction of multiple design iterations and trials. While students can design more in less time, learning gains are not always apparent (Klahr et al., 2007; Svarovsky and Shaffer, 2007)

These studies demonstrate that design-based science instruction helps students integrate abstract thinking into concrete applications (Roth 1996, 2001). Students can 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 needs to be set aside for students to share their ideas with each other (Fortus et al., 2004; Hmelo et al., 2000; Puntambekar & Kolodner, 2005). The social environment of the school, however, has an impact on the ways students respond to learning in this fashion. Students come to school with a variety of academic, personal, family, or social problems that can interfere with learning (Roth, 2001; Seiler et al., 2001). Changes in attitudes toward science do not always occur, and changes in science knowledge do not always occur either, although it is possible (Mamlok et al., 2001;
McRobbie et al., 2004). However, whether students would have learned as much in a traditional classroom is often unclear (Fortus et al., 2004; LaChapelle & Cunningham, 2007). Table 1 provides a brief summary of the studies.
Table 1

Summary of the studies

<table>
<thead>
<tr>
<th>CITATION</th>
<th>LEVEL</th>
<th>SUBJECT</th>
<th>DURATION</th>
<th>ASSESSMENT</th>
<th>CONTROL?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roth, 1996</td>
<td>Elem.</td>
<td>Structures</td>
<td>13 weeks</td>
<td>informal, design</td>
<td>no</td>
</tr>
<tr>
<td>Penner, Giles, Lehrer, &amp; Schauble, 1997</td>
<td>Elem.</td>
<td>Models/ Elbow</td>
<td>3 hours</td>
<td>interview: models</td>
<td>yes</td>
</tr>
<tr>
<td>Penner, Lehrer, &amp; Schauble, 1998</td>
<td>Elem.</td>
<td>Models/ Elbow/Levers</td>
<td>3-4 hours</td>
<td>informal, science</td>
<td>no</td>
</tr>
<tr>
<td>McRobbie, Stein, &amp; Ginns, 2000</td>
<td>Middle</td>
<td>Boats</td>
<td>Not reported</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Hmelo, Holton, &amp; Kolodner, 2000</td>
<td>Middle</td>
<td>Models/ Lungs</td>
<td>2.5 weeks</td>
<td>yes: science</td>
<td>yes</td>
</tr>
<tr>
<td>Seiler, Tobin, &amp; Sokolic, 2001</td>
<td>High</td>
<td>Cars</td>
<td>6 hours</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Roth, 2001</td>
<td>Middle</td>
<td>Machines</td>
<td>4 months</td>
<td>yes: science and attitudes</td>
<td>no</td>
</tr>
<tr>
<td>Mamlok, Dershimer, Fortus, Krajcik, &amp; Marx, 2001</td>
<td>High</td>
<td>Cellphones</td>
<td>9 weeks/ 5 weeks</td>
<td>yes: science and attitudes toward science</td>
<td>no</td>
</tr>
<tr>
<td>Kolodner, Gray, &amp; Fasse, 2003</td>
<td>Middle</td>
<td>Vehicles</td>
<td>8 weeks</td>
<td>yes: process skills</td>
<td>yes</td>
</tr>
<tr>
<td>Fortus, Dershimer, Krajcik, Marx, &amp; Mamlok-Naaman, 2004</td>
<td>High</td>
<td>Structures/ Cellphones/ Batteries</td>
<td>17.5 weeks</td>
<td>yes: science</td>
<td>no</td>
</tr>
<tr>
<td>Puntambekar &amp; Kolodner, 2005</td>
<td>Middle</td>
<td>Erosion</td>
<td>3 weeks/ 5 weeks</td>
<td>yes: scientific understanding</td>
<td>no</td>
</tr>
<tr>
<td>Klahr, Triona, &amp; Williams, 2007</td>
<td>Middle</td>
<td>Mousetrap Car</td>
<td>Not reported</td>
<td>yes: design</td>
<td>yes</td>
</tr>
<tr>
<td>Svarovsky &amp; Shaffer, 2007</td>
<td>Middle</td>
<td>Structures</td>
<td>10 hours</td>
<td>interview: design and center of mass</td>
<td>no</td>
</tr>
<tr>
<td>Lachapelle &amp; Cunningham, 2007</td>
<td>Elem.</td>
<td>Water Filters/ Pollination</td>
<td>Not reported</td>
<td>yes: design and science</td>
<td>yes</td>
</tr>
<tr>
<td>Silk, Schunn, &amp; Cary, 2007</td>
<td>Middle</td>
<td>Electricity</td>
<td>6 weeks</td>
<td>yes: science reasoning</td>
<td>yes</td>
</tr>
<tr>
<td>Mehalik, Doppelt, &amp; Schuun, 2008</td>
<td>Middle</td>
<td>Electricity</td>
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</tr>
</tbody>
</table>
Summary of Literature on Alternative Conceptions of Heat and Temperature

Students' alternative conceptions of heat and temperature begin at a young age and persist through school (Albert, 1978; Clough & Driver, 1985; Erickson, 1979, 1980, Paik et al, 2007). Because of the young age at which children experience warmth, experience being cold, and experience touching hot or cold things, alternative conceptions of heat, temperature and heat transfer are often resistant to change. Vosniadou et al. (2001) explain that even young children intuitively develop a "framework theory of physics" to describe and explain the world they experience. The once-popular caloric theory that heat is a substance made of particles that flow still dominates children's thinking, and they rely on their senses to measure temperature, not understanding the kinetic theory and its implications in heat transfer. The belief that cold is a substance that moves is prevalent with middle and high school students. These students also think that metal objects are naturally colder than plastic ones because metal attracts the cold. The directionality of heat transfer is not understood because heat is not seen to be a form of energy. Erickson (1979) recommends explicit activities to help students transform their alternative conceptions of heat and temperature. Without explicit interventions designed to target these alternative conceptions, chances are that they will persist into adulthood (Clough & Driver, 1985).

Summary of Literature on Instructional Interventions about Heat

These four studies demonstrate that computer simulations might be effective in helping students discard alternative conceptions of heat (Clarke & Jorde, 2004; Linn &
Lewis, 1994), although without control groups that do not use the simulations, it is impossible to determine the actual effect computer simulations have on conceptual change. Additionally, when a large amount of time is devoted in the classroom to one concept, it might not matter what instructional technique is employed (Lewis & Linn, 1994). Multiple types of assessment are important in understanding students' conceptions (Jones et al., 2000). When the only assessment is a short multiple-choice pencil and paper test, complete understandings cannot be gained. It is still unclear whether cooperative groups are beneficial in helping students deal with alternative conceptions, but showing students that different theories to explain heat have been used and discarded over time may help them discard their own scientifically-incorrect theories (Rogan, 1988).

Limitations of the Literature

Ten of the 16 studies about design-based science had positive findings, demonstrating that design-based science was successful in promoting science concept knowledge, design skills, scientific reasoning, or process skills, but the degree of what was deemed "positive" varied from study to study, and often the effect, while statistically significant, was not substantial. The remaining studies either did not describe the findings clearly, the findings were negative, or the findings were unclear.

Only seven of the studies had a control group for comparison, but in all cases, the control group students had different teachers and/or attended different schools. Therefore, the teacher effect could not be ruled out as a factor affecting the results.

While 11 studies included some sort of a pre- and posttest assessment, only five
studies included assessments of science content knowledge— the rest were about design, process skills, or scientific reasoning. None of the five assessments of science knowledge were valid or reliable instruments or at least validity and reliability information was not provided.

None of the 16 studies addressed students' alternative conceptions and conceptual change. Research was not conducted to determine the students' alternative conceptions. Literature was not reviewed for prior studies to determine students' alternative conceptions of the content.

Five studies reported only quantitative results. Only two studies used mixed methods for data collection and analysis, but in those studies, control group students had different teachers so the teacher effect could not be ruled out (Hmelo et al., 2000; Kolodner et al., 2003).

Finally, only 4 of the 16 studies used a theoretical framework to guide the methods of the study, but the degree to which the theoretical framework actually helped frame the design of the intervention, the type of data collected, or the analysis of the data was ambiguous. A theoretical framework serves as a base on which a study builds and a rationale for the research methods. It helps frame the type of questions that are to be asked, the methods for collecting data to answer the questions, and the types of data analysis conducted. Having a theoretical framework makes research more effective because the questions asked and data collection and analysis methods all tie back to a particular theory of learning (Bodner, 2007). While constructivism of some sort is the
most common theoretical framework used in science education research, hermeneutics and critical theory are also used. Hermeneutics is commonly used in qualitative research when the questions occur within specific contexts, particularly when language or text is being analyzed (Shane, 2007). Situated cognition is a type of hermeneutic theoretical framework. Critical theory is also used in science education research. It concerns issues of power and justice, looking at the factor that race or gender or socioeconomic status plays in education. Studies that operate within the theoretical framework of critical theory are often formative instead of summative, having a transformative effect on the classroom environment, empowering the participants to improve their position in society by giving them a voice (Mayo, 2007).

Roth (1996) used the theoretical framework of situated cognition in his study that had elementary students designing towers out of plastic straws. Situated cognition states that knowledge is acquired as a person interacts within a social environment- a community of practice- engaged in the authentic context of how that knowledge might be used (Lave & Wenger, 1991). Social constructivism was used as a theoretical framework in the Mamlok et al. (2001) study which had students designing cell phones on posterboard, in the Fortus et al. (2004) study which had students designing cellphones on posterboard in addition to batteries and model houses, and in the Puntambekar & Kolodner (2005) study which had students designing structures that prevented erosion in model stream banks.

While there were many studies which uncovered alternative conceptions possessed by children and adults, there were few interventions at the K-12 level which
were researched to address students' difficulty learning scientifically correct conceptions of thermal energy, temperature, heat transfer, and thermodynamics. No studies could be found which addressed students' alternative conceptions in any science content area through the use of design-based science.

Recommendations

Examining the results from these studies and their methodological features, it is clear that work in this area is incomplete. Learning science through design was not always shown to be a given. The findings were not consistently substantial, and many methodological weaknesses were common to them all.

Future research should use a mixture of quantitative and qualitative measures including open-ended student interviews and classroom observations. Researchers should utilize more than one or two classes of students, preferably at different academic levels, and incorporate a fair control group with the same teacher for comparison. Students in the control groups should be learning the same science concepts that students in the experimental groups are learning, ideally those described by state or national curriculum standards. Researchers should work within the framework of a learning theory, use reliable and valid instruments and interview protocols, and the design of the intervention should address students' alternative conceptions about science content instead of merely factual knowledge- something that none of the studies on design-based science accomplished.

Future research in the area of design-based science should be connected to a
theoretical framework of learning so that research questions, data collection and data analysis are appropriate, and so that results can be examined in light of the theory.

In this research, students learned about heat energy through a merger of the conceptual change model and engineering design. They used an Engineering Teaching Kit (ETK) called *Save the Penguins*, designed to help students learn about heat energy and heat transfer through demonstrations, examples, experiments, explanations, and the design, construction, and testing of a device meant to prevent heat transfer from melting a penguin-shaped ice cube. Students' conceptions of heat transfer were identified through pre and posttests, classroom observations of activities and discussions, pre and post interviews, and authentic assessment mediated through the design challenge. Wandersee, Mintzes, and Novak (1994) advise that studies designed to address conceptual change through an intervention of some sort need to rely on more than pencil and paper tests for student evaluation. They call for "rigorous, well-controlled studies" which measure subtle changes in students' understandings. This study met that challenge. The purpose of the research was to better understand how middle school students might learn significant science concepts at a deep conceptual level and develop better attitudes toward and understandings about engineering through an engineering design challenge that encouraged the application of scientific understandings. The research questions guiding the investigation were:

1) How might students' conceptions about thermal energy and heat transfer differ before, during, and after engineering design-based instruction and typical instruction on the topics of thermal energy and heat transfer?
2) How might students' conceptions about and attitudes toward engineering differ before, during, and after learning heat transfer and thermal energy through an engineering design challenge?

3) How might an engineering design challenge specifically change students' conceptions of thermal energy and heat transfer?

Theoretical Framework

The central features of this research were: problem solving through authentic tasks, acknowledgement and treatment of alternative conceptions, working within social groups or learning communities, creating artifacts that represent knowledge, and coaching or scaffolding by a teacher or more knowledgeable person (Krajcik & Czerniak, 2007). These features map neatly to the theoretical framework of learning called social constructivism.

Social constructivism is a perspective which began with a focus on the early 20th century ideas of Soviet psychologist Lev Vygotsky and Swiss psychologist Jean Piaget. The social constructivist perspective on education stresses that students should play an active role in their own learning, working together to solve problems, discussing and debating, while cooperating at the same time. The role of the teacher should be that of a facilitator, and the teacher takes a very 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 (Palincsar, 1998; Tobin & Tippins, 1993).
Working within social groups

In Lev Vygotsky's book, *Mind in Society* (1978), the emphasis is placed on how social groups can help a student accomplish more that he or she would have been able to accomplish alone. Vygotsky wrote that the zone of proximal development (ZPD) describes the distance between what a student is capable of mastering alone and what he or she is capable of mastering with the help of others. “What children can do with the assistance of others might be in some sense even more indicative of their mental development than what they can do alone” (p. 85).

The old adage states that “two heads are better than one”, and in social constructivism, the theory implies that groups of learners indeed can accomplish more than they could have individually. 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” (p.90).

While Bandura (1977) stated that learning often occurs by simply watching others performing tasks, and Bell, Grossen, & Perret-Clermont (1985) found that when children worked with their peers, they did indeed demonstrate more cognitive growth than when they worked alone, the children had to all participate. If one child in the group was of a higher cognitive level, he or she might dominate and the other peers would be submissive and not learn as much. Forman and Kraker (1985) reported that social status also plays a role in group dynamics. A more socially dominant child might invoke passive compliance of the other group members. This presents challenges for the teacher when
grouping students for active collaboration in a constructivist classroom. Damon (1984) theorized that when new skills are to be learned, working with a more cognitively advanced person could be beneficial, but when children are working on gaining new perspectives, active peer collaboration is superior.

In this study, students worked together in social groups of 3 or 4. Instead of randomly assigning students to groups, or letting them pick teams (potentially leaving some students behind), student groups were chosen by the teacher to make sure that group dynamics would be optimized by careful consideration to the social status, cognitive levels, and personalities of each group member. The intervention took place 3 weeks into the school year so that the teacher had time to get to know the students and choose these groups purposefully. The researcher carefully examined group dynamics, group discussions, and how peer discourse was used to either further or halt the progress of conceptual change.

*The more knowledgeable other*

These ideas blend well with Vygotsky’s notion of scaffolding provided by a “more knowledgeable other” (Vygotsky, 1978). This “more knowledgeable other” helps the learner transverse the zone of proximal development from a place where the task at hand is too intellectually challenging to a place where the learner is comfortable. In a classroom, more advanced peers can serve in this function, but often it is the teacher who can best take on this role. Through modeling, coaching, breaking down large tasks into smaller ones, making complex ideas easier to understand, or pointing out essential
elements of a concept, a teacher creates the scaffolding to help a struggling learner succeed (Krajcik & Czerniak, 2007).

Design-based science learning reflects the social constructivist theory of learning by having students work collaboratively in groups to solve problems and construct solutions, but learn certain skills through the modeling of their teacher. When students are involved in engineering design-based activities, they are not being told what to do—they are creating and innovating, making decisions with their peers based on their underlying knowledge. The role of the teacher is to guide students through their decision-making processes and model new skills to be learned. An art teacher would lose credibility if she painted all her students’ work for them. In this same way, the science teacher should allow students to make mistakes, test and try their ideas, all the while modeling skills and behavior, and shepherding them along so they won’t lose their way. In design-based science activities, student teams at first work collaboratively, and then share their knowledge with the larger classroom community.

In this study, the teacher served as the more knowledgeable other, but even students and student teams served in this capacity as all groups took advantage of the knowledge that resulted from the groups’ trials and experiments.

Creating artifacts

Although some rightfully argue that designing a device does not necessarily require a student to apply scientific principles, designed artifacts can be tangible representations of what a student understands (Sadler, Coyle, & Schwartz, 2000).
Vygotsky (1978) theorized that all human action is mediated by tools and signs. These signs can be language, diagrams, drawings, or text. Tools broaden the range of an individual’s activities and thus increase psychological functions. From a social constructivist point of view, the most important tool for cognitive development is discourse (Palincsar, 1998). Through cooperative discourse, students can change their conceptions from alternative to scientific.

It is argued that conversational interaction provides a means for students to construct increasingly sophisticated approximations to scientific concepts collaboratively, through gradual refinement of ambiguous, figurative, partial meanings (Roschelle, 1992, p. 237).

When tools and signs are both used, individuals operate with higher psychological function and behavior. In design-based science activities, students use both tools and signs to design, create, and test devices or “artifacts.” Papert (1980) says that artifacts can be “objects to think with” because they make abstract concepts concrete and tangible. Artifacts are shared and critiqued by others, and as a result, students have many opportunities to use artifacts to reflect on what they know (Krajcik & Czerniak, 2007). Designed and created artifacts can move a student’s thinking into the concrete world, and in doing so, free up mental resources for developing more complex ideas (Roth, 2001). In design-based science activities, the artifact is the central focus, the culminating achievement, and the tangible method of demonstrating an understanding of heat transfer. It is where tools and signs converge under a mediated activity. Every component of the designed device is serves a real purpose and has the potential to reflect some scientific knowledge.
In this study, the designed, constructed, and tested "ice-penguin dwelling" served as the artifact students used as an object to think with. These dwellings were shared and critiqued by others, and each design decision was explicated by group members, subject to review by peers and teacher alike. The artifact also served as a form of authentic assessment by the researcher, who used it during interviews to help understand how students applied their knowledge of thermal energy and heat transfer to design.

*Scaffolding by a teacher*

Through engineering design activities, students should be able to create their own knowledge of scientific principles through active manipulation and testing of materials and ideas. But because students come to school with their own understandings about the world and how it works, their understandings may not resemble those of scientists. The teacher must provide the opportunities for students to challenge and internally modify their prior beliefs. Therefore, social constructivists see that the role of the teacher is to help learners construct their knowledge through scaffolding and coaching (Scott, Asoko, & Driver, 1991). Social constructivists see that learners construct meaning through active engagement, not passive listening. Learners use and apply their knowledge to carry out investigations and create artifacts that represent their understanding. Learners work within a social context as they use language to express and debate their ideas. Learners engage in authentic tasks that are relevant to the student and connected with their lives outside of the school setting. The theoretical framework of social constructivism provides a lens with which to view this research, and a means with which to test it.
In this study, the teacher acted as guide and coach; she did not didactically delivering content, but involved students in phenomena, discussions, questioning strategies, and helped students design their experiments as they prepared to construct and test their artifacts. When students were interviewed by the researcher, the open-ended nature of the questions allowed for some scaffolding too, in order to determine what students could explain on their own as opposed to what they could explain with the help of a guide and coach.

*Problem solving through authentic tasks*

Additionally, research has shown that students who have greater interest in what they are learning will process information at deeper levels (Brophy, 1998; Schiefele, 1991; Hidi, 1990). In design-based science activities, the teacher does not tell the students what to build. Instead, the teacher steps back and allows the students to take the primary lead in their own learning. Problem solving through authentic tasks that relate to students' lives should serve to increase student interest and deeper conceptual knowledge.

In the case of the *Save the Penguin* ETK, the broad context is global warming. Students learn that the energy we use to heat and cool our houses comes from power plants, most of which use fossil fuels to convert chemical energy to electrical energy. The burning of fossil fuels has been linked to increased levels of carbon dioxide in the atmosphere, which in turn has been linked to increases in global temperature. This change in temperature has widespread effects upon life on Earth. Penguins live in the southern hemisphere, primarily on the icy continent of Antarctica. As the Earth warms
and ice melts, penguins lose habitat. Therefore, students see that better-designed houses
that use less energy for heating and cooling have an effect on penguins. Energy efficient
houses that minimize unnecessary heat transfer will draw less electricity from the fossil
fuel burning power plants and not contribute as much to global warming.

Summary

The theoretical framework of social constructivism informed this study in terms
of the design of the study, the treatment, and the evaluation of student learning and
attitudes. Students worked in collaborative groups to solve an authentic problem that
related to their lives. The teacher served as facilitator, “more knowledgeable other”, and
scaffolding support. Students were assessed through conversational interviews and
authentic assessments as well as traditional pencil and paper tests. Students’ alternative
conceptions of thermal energy and heat transfer were assessed prior to instruction, and
specific interventions were used to target them, allowing students the opportunity to
become dissatisfied with their prior conceptions in favor of more scientific ones. A
control group was used to assess the degree to which design impacts conceptual change,
but even in the control group, social constructivism reigned as the framework for
teaching and assessment, and students had equal opportunities to learn the objectives,
through methods such as projects, experiments, or computer simulations, instead of
engineering design. This theoretical framework will be tied more closely to the research
methodology at the end of Chapter 3.
CHAPTER 3: METHODOLOGY

Purpose

Reforms in science education emphasize student-centered classrooms where inquiry is a primary vehicle for learning (AAAS, 1993; NRC, 1996). Engineering design projects have been shown to be one instructional approach that can support the inquiry style of active learning (Hmelo, Holton, & Kolodner, 2000; Lachapelle & Cunningham, 2007). However, studies on how teachers use design projects to help students understand the content knowledge and methods of science have mixed results. While there is good evidence to suggest that design-based science is a valuable tool for science teachers and learners, there is a need for more research in this area. Specifically, the question remains as to whether design activities can be used to help promote deep conceptual scientific understanding. In this chapter, the methods for approaching this question and others will be outlined.

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. In this study, pre and posttests, interviews, and classroom observations were used to assess the relationship between the type of activities used to instruct students and science concept understanding, and attitude toward and knowledge about engineering. At the same time, the ways in which design
activities helped students engage in science concepts were explored using observations, discourse analysis, interviews, and artifact analysis.

The research questions guiding the investigation were:

1) How might students’ conceptions about thermal energy and heat transfer differ before, during, and after engineering design-based instruction and typical instruction on the topics of thermal energy and heat transfer?

2) How might students’ conceptions about and attitudes toward engineering differ before, during, and after learning heat transfer and thermal energy through an engineering design challenge?

3) How might an engineering design challenge specifically change 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.

Method

This investigation features a mixed methods approach to data collection and analysis. A mixed methods approach combines qualitative and quantitative research methods. In this case, a control group will be used for comparison, and a wide variety of data will be collected. The purpose of using a mixed methods approach is to increase the internal validity of assertions through triangulation of all data sources. Since all research methods have limitations, the biases in one method can neutralize the biases in the other
method. Additionally, the results from each method can be used to confirm or corroborate findings from the other (Creswell, 2003). This form of research poses challenges for the researcher, as a wide variety of data sources are collected, and extensive time is required to analyze both textual and numeric data. The researcher must also be competent in both types of research methods. Data sources include two different student pre- and posttests, open-ended interviews with students both before and after the intervention, direct observations of the participants during the classroom intervention, video and audio records of participants' behaviors and conversations during the intervention, artifacts created by the participants, and open-ended interviews with the teacher participant prior to, during, and after the intervention. The study can best be described as mixed methods using the concurrent triangulation strategy (Creswell, 2003).

Treatment

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 (VMSEEI), but was subsequently revised and re-written by the researcher after pilot testing. See Appendix A for the complete curriculum. It was chosen as the treatment after a pilot study conducted in the fall of 2007 demonstrated that it was well received by students and teachers. In this section, the VMSEEI program, the *Save the Penguins* Engineering Teaching Kit (ETK), the pilot study conducted in the fall of 2007, and the rationale for choosing the *Save the Penguins*
Penguins ETK for the dissertation research will be described.

The VMSEEI

The VMSEEI was founded at the University of Virginia in 2002 by faculty from the Department of Mechanical and Aerospace Engineering and the Curry School of Education with help from grants provided by the Payne Family Foundation and the National Science Foundation. The four major objectives of the VMSEEI are to:

1. Educate middle school teachers and student teachers about how to introduce engineering and technology in their classes;

2. Promote awareness and stimulate excitement among middle school students concerning the nature and practice of the engineering profession;

3. Help students develop an appreciation for the tradeoffs involved in the practice of engineering, and an understanding for how engineering decisions impact society and the environment; and

4. Attract women and minority students to engineering, mathematics, and science.

(Richards, Bart-Smith, Laufer, Humphrey, Bell, & Tai, 2003).

The goals of the VMSEEI are played out as undergraduate mechanical engineering students and science education students at the University of Virginia take a course in which they design middle school science and math curricula that use engineering design challenges as a central theme. This design course has been taught for over 5 years by Professor Larry Richards, and so far, over 30 different ETKs have been
designed and used by local teachers with more than 2000 middle school students (Richards, Flaherty, & Cunningham, 2004; Richards, Hallock, & Schnittka, 2007). Some examples of ETKs that have been popular in classrooms are: Under Pressure: Designing submersible vehicles, RaPower: Designing and building model solar cars, Catapults in Action: Designing catapults for distance and accuracy, HoverHoos: Hovercraft design, and Save the Penguins: Designing a structure to prevent heat transfer.

Overview: Save the Penguins ETK

The Save the Penguins ETK as re-written by the researcher 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 and a presentation about a diverse group of engineers and the variety of goals they have to make the world a better place. 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 (Erickson & Tiberghien, 1985). 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 (Knight & Cunningham, 2004). 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 idea that increasing interest and motivation can have a positive impact on the quality of learning is not unique or new (Schiefele, 1991). Classroom boredom has been well documented, and it may be a symptom of a bigger problem: lack of motivation to learn (Mitchell, 1993). Students are not bored as they actively participate in an engineering design activity which is neither too challenging nor too simplistic. This intervention has the potential to increase student interest and motivation in science and engineering as student groups take ownership for their ideas and their designs, and as they learn about how better engineered dwellings have the capability to improve the health of the environment in which they live.

The Curriculum: Save the Penguins ETK

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, the *National Science Education Standards*, and the *Benchmarks for Science Literacy*, and placed in order from the simplest behavior to the most complex on Bloom's taxonomy scale (Bloom, 1956; Virginia Department of Education, 2003; NRC, 1996; AAAS, 1993). They can be found in Appendix B. The state and national standards related to heat energy and heat transfer can be found in Appendix C.

The *Save the Penguins* ETK curriculum is outlined in Figure 1 and described in detail in Appendix A. 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 (Lemke, 1990)." 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.

Figure 1. Sequence of events in the curriculum.
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:

a) bubble wrap,
b) aluminum foil,
c) colored construction paper,
d) colored foam sheets,
e) Mylar film,
f) wooden sticks,
g) cotton balls, and
h) 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.

Students perform experiments on different materials or combinations of materials
prior to designing their dwelling. 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.

As students purchase materials and design their dwelling, the teacher walks from group to group providing support, asking important thought questions, and quizzing students on why particular building materials may block heat transfer. Students keep a
story board poster of their design process. The teacher can quickly glance at what student
groups are doing and thinking, and student groups can learn from each other.

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 are present so students can 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 Pilot Study

The purpose of the pilot study.

In the fall of 2007, the researcher conducted a pilot study with 3 teachers and their students (Schnittka & Richards, 2008). The purpose of the pilot study was to become familiar with the Save the Penguins ETK and improve the curriculum. Specifically, the study addressed the following questions:

1. Do the teachers find the Save the Penguins ETK to be valuable and engaging?

2. Do the students find the Save the Penguins ETK to be valuable and engaging?

3. What implementation issues exist for the Save the Penguins ETK in a middle school classroom?

The participants in the pilot study.
The pilot study was conducted at Beauregard Middle School\textsuperscript{2}, a rural county middle school in a Mid-Atlantic state. It was selected for this pilot study based on its diverse student population, proximity to the researcher's home, and positive relationships established with the administration and staff. Beauregard Middle School had 49 teachers and 419 students enrolled in grades 6-8 during the 2007-08 calendar year, with 13\% of students being African American, 4\% Hispanic, 16\% in Special Education, 4\% Limited English Proficiency, and with 31\% eligible for free or reduced lunch.\textsuperscript{3} At Beauregard, a year of science is compressed into one semester, with students meeting daily for an 80-minute block.

\textit{Methods of the pilot study.}

The \textit{Save the Penguins} ETK was used in five middle school classrooms with 3 teachers: Cathy, Stacey, and Judith. After the \textit{Save the Penguins} ETK was used in each class, students were administered a survey (Appendix D). The evaluation survey was originally designed by a student team of mechanical engineering students at the University of Virginia in 2006 for an ETK they developed on making headphone speakers. The survey was modified for the \textit{Save the Penguins} ETK. Each survey consisted of 10 Likert-scale questions and three open-ended questions. The Likert-scale questions were about teamwork, the design process, content, perceived learning, fun, challenge, and success. The open-ended questions elicited responses about what students

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\textsuperscript{2} The name of the school and of the teachers at the school are pseudonyms.

\textsuperscript{3} \url{http://www.greatschools.net}
learned, what they liked about the ETK and what they disliked. Student evaluation surveys were distributed on the last day that the teacher used the ETK. The immediacy of students’ completing the survey took advantage of their memories and reactions to the science lessons, design activities and the design challenge. The surveys were completed anonymously. The researcher assigned each survey a code number and entered the data into an Excel spreadsheet for analysis.

The teachers were interviewed about their impressions of the ETK, while suggestions for modifications to the curriculum and perceptions of student engagement and learning were elicited (Appendix E). The interview protocol was developed and pilot tested in a previous study which examined teachers’ impressions of newly-developed and field-tested ETKs (Richards & Schnittka, 2007). The set of seven questions provided a framework for the interview, but the interviewer made extensive use of follow-up questions to elicit more thoughts and ideas. Additionally, each teacher showed the interviewer examples of student work and told stories about students and teams of students who had participated in the engineering design activities. All the interviews were audiotaped and transcribed for analysis. Interviews lasted approximately 30 minutes.

Data analysis followed an analytic induction process as described by Erickson (1986). The researcher reviewed the data sources with the goal of characterizing how the ETK was perceived by students and teachers. The *Save the Penguins* ETK was first used by teacher Cathy in one medium-level science classroom of 24 sixth grade students. Improvements to the curriculum were made, and then the *Save the Penguins* ETK was used by teacher Stacey in one additional sixth grade class. After further improvements the
ETK was used by teacher Judith in three eighth grade classes of different academic levels.

*Implementation issues*

Cathy remarked that the curriculum did a good job of helping students learn about radiation and convection, but that it needed something more to help students learn conduction since the ice cube was supposed to rest on a plastic mesh taped to the top of a plastic cup. She also became frustrated cutting materials to sell to students, and suggested that materials be pre-cut for ease of quick "selling".

Stacey implemented several of these suggestions. She pre-cut the materials for easy distribution, but did not think of a way to solve the problem of heat conduction lacking in the ice cube melting process. She said that one downside to the way the lessons were designed was that students did not have to directly link which construction material may have affected which type of heat transfer.

Judith implemented all the suggested modifications during her use of the ETK. Since it was cold outside by the time she tested the curriculum, she used a pre-heated black countertop in her classroom with a heat lamp to simulate the asphalt outside, and had students rest their ice cube penguin on a small piece of paper directly on the heated surface. This provided both radiant heat from above in the form of an incandescent lamp, radiant heat from the black counter below, and conduction as the ice cube was almost in direct contact with the heated counter.
Results of the pilot study.

Did the teachers find the *Save the Penguins* ETK to be valuable and engaging?

All 3 teachers who used the ETK remarked that using the curriculum increased student engagement and learning during the course of the intervention. Stacey remarked that her low-level students were more willing to “stick their necks out” with the *Save the Penguins* curriculum, and that doing the design activities was not as threatening to them as reading or writing. “They were actively participating, not reading or writing which is one of their weaknesses.” Judith remarked that her students were all very engaged in the design and testing process during the *Save the Penguins* ETK. She said that engagement was the greatest benefit of using the curriculum with her students.

It was fun. It was just fun. That’s important to me that they see science as being fun and I think that’s one of the most important things to me and they did retain what they learned and they took it outside of the classroom and talked to their parents. (Judith, Exit Interview)

Did the students find the ETKs to be valuable and engaging? On a scale from 1 to 10, students were asked how much they enjoyed the ETK experience. The mean score that 99 students gave the *Save the Penguins* curriculum was 8.34 out of a possible 10 points. When asked, “What was the best part of this experience?” making the device and participating in the design competition were clearly the students’ favorite parts of the unit of study. Twenty six percent of students reported that the worst part of the *Save the Penguin* ETK experience was losing the final design challenge. Working with members of their team and creating a poster were also facets rated poorly by students.

Judith expressed concern that students did not always link their choice of building
material with blocking a particular type of heat transfer, and suggested that students graphically illustrate this on their posters. Students in these classes reported not enjoying the poster-making part of the activity more so than students of other teachers. Since Judith had students create posters at the end of the unit and the other teachers had students work on them as they designed, tested, and constructed the devices, students in the dissertation study used the posters as ongoing storyboards, not only to help students keep track of their ideas and experiments and designs as they progress through the unit, but to inform other student groups and the teacher as well.

Overall, students reported greater satisfaction with teamwork when they self-selected their teammates. Since 26% of students answered the question, “What was the worst part about this experience?” with the answer, “losing,” the dissertation study took advantage of students’ intrinsic motivation to improve their designs relative to their own starting point rather than to an extrinsic motivation to compete against other student groups (Sadler, Coyle, & Schwartz; 2000). The final design challenge allowed all student groups to compare their final products to earlier iterations.

Procedure

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 attitudes toward and knowledge about engineering through an engineering design challenge that encourages the application of scientific understandings. The investigation took place in five phases. These phases will be briefly described below, and then in more detail.
detail in separate sections that follow. See Figure 3 for an overview.

Figure 3. Sequence of events in the study.

The first phase involved developing and modifying two instruments and interview protocols in order to provide evidence for their reliability and validity. The second phase involved finding and training a teacher participant, and then statistically comparing standardized test scores from students in her classes for the purpose of choosing which class of students (out of three) to comprise the control group, and which to comprise the
two experimental groups. During the third phase, the teacher and her classes were observed for the purpose of establishing a baseline for student behaviors and attitudes. Additionally, the teacher was interviewed in order to document her plans for the control and experimental groups. During phase four, pretests were administered in the three classes and a subset of students was interviewed for the purpose of establishing a baseline of attitudes toward science and engineering and conceptions of heat energy and heat transfer. In order to document student-student and student-teacher dialog and interactions, all classes participating in the study were observed during the intervention, which lasted for six 80 minute class sessions. So that differences in attitudes toward science and engineering and differences in conceptions of heat energy and heat transfer could be documented, posttests took place at the conclusion of the unit, and students were interviewed again. The final phase involved an exit interview with the teacher participant for the purpose of learning the teacher’s perspective on how the students responded to the study.

*Phase 1: Developing and testing the instruments and interview protocols.*

In this study, two different instruments and four different interview protocols were used. The two instruments administered both as pre- and posttests were:

1. Heat Transfer Evaluation (HTE)
2. Attitudes Toward Engineering Survey (ATES)

The four interview protocols were:

1. Teacher Entrance Interview Protocol
2. Student Entrance Interview Protocol
3. Student Exit Interview Protocol

4. Teacher Exit Interview Protocol

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 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 researcher worked with eighth grade students at Beauregard Middle School, university students, and panels of experts to determine evidence of validity and reliability for the instruments and interview protocols. Pre- and posttests were administered to eighth grade and university students, entrance and exit interviews were conducted with select students who use the ETK in the spring semester of 2008, and classroom observations took place with those groups of students in order to anticipate and correct for potential problems prior to the dissertation research.

Reliability and validity of instruments

Heat Transfer Evaluation.

After a comprehensive search, it was determined that an instrument did not exist which might measure the science content of this intervention, namely thermal energy and heat transfer through conduction, radiation and convection. Therefore, the researcher created a multiple choice instrument with 12 questions called the Heat Transfer Evaluation (HTE) (Appendix F). The science content assessment was informed by some
questions from the 26-item Thermal Concept Evaluation (TCE) designed for high school students (Yeo & Zadnik, 2001). This assessment was used because it reported evidence of validity and reliability and the fact that it contained well-written questions relevant to the topic of heat transfer. Five test items were chosen from the TCE and modified slightly. Other items were researcher-created based on the science content standards and objectives of the ETK and on thermal energy alternative conceptions research (Lewis & Linn, 1994; Erickson & Tiberghien, 1985; Driver, Squires, Rushworth, & Wood-Robinson, 1994). The TCE did not contain questions related to radiation, conduction through solids, convection, or heat transfer from something cold to something even colder. Questions were created to address these concepts, and multiple choice answers were created to target common alternative conceptions about heat, temperature, energy, insulators, conduction, convection, and radiation. The primary alternative conceptions addressed in the HTE are:

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.
5. Heat rises.
6. Aluminum foil is a good insulator for cold things.
7. Heat moves because it builds up in one place which cannot hold it.
8. Metals are naturally colder than non-metals.
9. Light colored or shiny objects absorb radiation.
The Thermal Concept Evaluation originally contained 26 items and was designed for students aged 15-18. Test reliability was determined using a split-half correlation which compared even numbered questions with odd numbered questions. The Spearman-Brown correlation coefficient was determined to be .81. The instrument was assessed for face and content validity by a group of physics professors, and students were also interviewed about their interpretation of the questions. Construct validity was "established through a detailed examination of the distribution of student selection of alternatives and through interviews with students" (p.500) and also by the performance of 458 students at four grade levels. The correlation between their performance on the test and the amount of exposure they had to thermodynamics instruction was computed, and the differences were statistically different ($p < .05$) with an effect size of .70.

There are several ways of assessing the validity of an instrument used in research, but the most relevant checks for this study are for face validity, content validity, and construct validity. The new 12-item multiple-choice science content instrument on heat transfer was assessed for evidence of face and content validity 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. Panel members were recruited through letters mailed to local high school teachers, science education doctoral students, and university professors. They were offered a modest financial incentive for reviewing the assessment. 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
content validity, the panel compared items from the assessment to the Virginia state standards for eighth grade science, the *National Science Education Standards*, and the *Benchmarks for Science Literacy*.

Construct validity is a measure of whether the instrument actually assesses the constructs, or particular concepts, defined by the researcher. In order to establish evidence for construct validity, the constructs must be understood, and they must be measured. An inference must be made about whether the instrument correctly measures these constructs. If the instrument correctly measures the constructs, then it should pass a differential-groups test. In this assessment, those who have knowledge of the constructs should be able to do well on the test while those without knowledge of the constructs should not do as well (Brown, 2000). Construct validity of the HTE was measured through differential groups and pre-posttests during the pilot study.

To assess construct validity, 59 eighth graders in the 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 $r = .62$. To further assess construct validity, this instrument was
administered to a group of 59 eighth grade students in the pilot study. It was expected that they would score significantly lower than the university students. Their mean score was 4.58 (Mdn = 4) out of 12 points, significantly different from both the engineering and other university students at $p < .001$ with an effect size $r = .83$ when compared to engineering students and an effect size $r = .49$ when compared to the other university students. See Figure 4.

![Figure 4. Mean scores on heat transfer evaluation](image)

A Kruskal-Wallis test demonstrated that all three means were statistically different from one another at $p < .001$. Differences between the three groups were statistically significant and substantial. Differences between the two adult groups demonstrated that knowledge of the construct alone, not reading ability or age, determined the difference.
There are several methods for providing evidence of reliability. For educational research, a reliability of .70 for instruments is generally considered adequate (Nunnally, 1978; Siegle, 2008), but a reliability of .60 is acceptable (Murphy & Davidshofer, 1988). The most common method of determining reliability is called test-retest (Gall, Gall, & Borg, 2003). This method was used to establish reliability for the 12-item Heat Transfer Evaluation. A group of 54 eighth grade students in the pilot study studying history at Beauregard Middle School who were not being exposed to the concepts of heat transfer 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.

*Attitudes toward Engineering Survey.*

The original Attitudes towards Engineering survey contained 25 Likert-scale items about engineering and what engineers do (Robinson, Fadali, Carr, & Maddux, 1999; Robinson & Maddux, 1999). It was originally designed for secondary math and science teachers who had participated in an engineering design course, but it was also used in four high school science classes after slight modification. Ideas for items were solicited from working engineers, engineering professors, and one science education professor. Robinson et al. (1999) tested the instrument with a group of 33 high school students who had participated in a three-week engineering unit and a group of 31 high school students who had not. The posttest scores from the experimental class were significantly higher than that the pretest scores ($p = .008$), which provided some evidence
for construct validity. The pretest mean was 3.90 out of a possible 5 points and the posttest mean was 4.12. Pre- and posttest means from the control class were not significantly different ($p = .188$), which provided some evidence for reliability. These means were 3.72 and 3.69, respectively. Reliability was not reported, nor was it measured (C. Maddux, personal communication, Feb. 20, 2008).

For the present investigation, a panel of six engineering experts examined the original survey of engineering attitudes and worked to modify the instrument from its original version, which was designed for high school science students. The engineers: three electrical, one industrial, and two mechanical, each had an average of 18 years’ experience working as engineers. Panel members were recruited through letters mailed to four practicing engineers and two retired engineers, all of whom had previous experience with middle school students. The modified instrument was assessed for face and content validity by this panel of engineers who reviewed the instrument to determine if it sufficiently covered attitudes middle school students might have about engineers. The assessment was continually modified according to the panel's suggestions, and further rounds of review and modification took place until 100% agreement was obtained for the wording and inclusion of each test item. Five test items were eliminated due to their irrelevance and out-of-date nature, the wording was changed on many items to reflect middle school students’ lives, several items were re-written to reflect a positive view of engineering, and two items were added resulting in the first version of the Attitude toward Engineering Survey (ATES) instrument. It contained 22 items.

Evidence of reliability for this first version of the ATES was ascertained through
measuring Cronbach’s alpha (Cronbach, 1951). A group of 54 eighth grade students in
the pilot study from three classes studying history at Beauregard Middle School and a
group of 62 mechanical engineering students from two university classes took the test.
The coefficient of reliability Cronbach’s alpha to measure internal consistency was
calculated to be .62 for the eighth grade history students and .70 for the engineering
students. This is an acceptable range of values according to Nunnally (1978) and Murphy

Reliability for the engineering students was taken as a more valid measure since
engineering students are most likely understand engineering enough to report valid
attitudes, while eight grade students may have not reported attitudes based on correct
conceptions of engineering. For additional reliability evidence, scores from the 22-item
test were compared across the two engineering classes (n = 37 and n = 25). The
difference was not significant (p = .127) and the means were 4.14 and 4.27 respectively.
The scores from the 22-item test were compared across the three eighth grade classes in
the pilot study (n = 15, n = 16, n = 23). The difference was not significant (p = .310) and
the means were 3.30, 3.19, and 3.09 respectively.

The length of the ATES may have been a factor in establishing reliability. Some
of the eighth grade students just circled all threes, indicating that they did not even read
the items. The ATES was subsequently shortened for the dissertation study to an 11-item
instrument (See Appendix G). In the dissertation study, 43 eighth grade students took the
ATES as a posttest after exposure to engineering design activities, and these scores
indicated a Cronbach’s alpha reliability of .79 while the 27 students who were not
exposed to engineering design activities took the ATES as a posttest and their scores indicated a Cronbach's alpha reliability of .82.

To assess construct validity, results were compared with separate tests of statistical significance. Construct validity was assumed because engineering students' attitude scores were significantly and substantially higher than the other university students' scores. For the 11-item sub-test with a range from 1 to 5 where 1 represents a very negative attitude toward engineering, 3 represents a neutral attitude and 5 represents the highest possible attitude, the mean for the 62 engineering students on the 11-item survey was 4.14, the mean for the 24 other university students was 3.54, and the mean for the 54 eighth graders in the pilot study was 3.14. A t-test comparing the two adult groups showed that they were significantly different at $p < .001$ with an effect size of .63. A t-test comparing the eighth grade students in the pilot study with the other university students showed that they were significantly different at $p < .001$ with an effect size of .44. Figure 5 demonstrates engineering attitudes held by adolescents, engineering students, and other university students. An independent one-way ANOVA demonstrated that the means between the three groups were significantly different ($p < .001$) with an effect size of .66. The range of expected values for students in the dissertation study was thus established to be between 3.14 and 4.14 points on a 5 point Likert scale.
Development and testing of interview protocols

The purpose for the teacher entrance interview in the dissertation study was to establish a profile for how the teacher viewed her teaching, what her perspective was on inquiry-based teaching, what her goals were for teaching heat transfer, and what her thoughts and feelings were about teaching science through engineering design. The purpose for interviewing the teacher again after the study was to find out whether she thought her goals were met, whether she saw a difference in student learning, motivation, or engagement between the control and experimental group, whether her thoughts and feelings about design-based science had changed, and whether or not she planned to continue to pursue teaching science through design.

The questions for the Teacher Entrance Interview and Teacher Exit Interview
were based on the dissertation research of Blackburn-Morrison (2005) because she investigated teachers' definitions, beliefs, and practices implementing inquiry-based science activities, in addition to the barriers to and facilitators of successful implementation (Appendices I and L). The interview protocols were validated by the panel of experts in the field of physical science education and research methodology who reviewed the interview protocols for their clarity, comprehensiveness, and relevance. The interview protocols were modified according to the panel's suggestions until 100% agreement was obtained for the wording and inclusion each question.

The purpose for interviewing students in the dissertation study prior to instruction was to find out what their conceptions of heat transfer were. A paper and pencil test can only tell so much, and an open-ended interview can elicit much more depth of understanding. Also, the entrance interviews provided the student's baseline opinion about their attitudes toward and understandings about engineering. The purpose of interviewing students after instruction was to find out how their conceptions of heat transfer may have changed. Additionally, students in the experimental group were asked to defend the design decisions they made for their penguin dwelling.

The interview protocols for the Student Entrance Interview and the Student Exit Interview (Appendices J and K) were developed by the researcher based on her experience in two other studies of student conceptions in science, and were validated by the panel of experts in the field of science education who reviewed the protocols for their clarity, comprehensiveness, and relevance. The interview protocols were modified according to the panel's suggestions until 100% agreement was obtained for the wording
and inclusion of each question.

Phase 2: Choosing the Site, Teacher Participant, and the Experimental Groups

The teacher participant in this dissertation study was chosen due to her interest in using engineering design activities and cooperative learning, and her reputation in the county as a dynamic, new middle school teacher. In order to train the teacher prior to the dissertation research, she used a truncated version of the Save the Penguins ETK with one class of students in spring 2008 in cooperation with the researcher.

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, Clare 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

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4 All names of people and places are pseudonyms.
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\(^5\) 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.

**The Researcher as Instrument**

In interpretive research, the biases, experiences, and values of the researcher are important in shaping the subjective analyses and theories that emerge. This background not only validates the credibility and qualifications of the researcher, but as well exposes any personal preconceptions the researcher may have going into the study (Creswell,

\(^5\) Data reported in the latest annual progress report for the county
In this study, my credibility as researcher-as-instrument comes not only from 10 years of experience as a middle school science teacher, but from my education in mechanical engineering. In 1986 I received a bachelor’s degree in mechanical engineering from Auburn University. While a student at Auburn, I was involved in cooperative education and worked for IBM in Research Triangle Park, North Carolina for six quarters as an engineer-in-training. This hands-on experience drove home the idea that applying the ideas I was learning in engineering school to real-world applications helped me learn the basic concepts with deeper understanding. In 1992, I received a master’s degree in mechanical engineering from the University of Virginia and my academic advisor was Professor Larry Richards, founding member of the VMSEEI. In 1995, I helped found Village School in Charlottesville, Virginia, a middle school for girls. One of my goals as a science teacher was to integrate engineering design activities into the science curriculum- not only to expose young women to careers in engineering, but to enhance their science education by providing them with real-world applications. As a public school teacher later on, I helped develop Engineering Teaching Kits for the VMSEEI and used some previously developed by the VMSEEI in my curriculum.

These experiences which reinforce my credibility in doing research on engineering education at the middle school level may also bias me toward favoring engineering-based curricula. My observations and interpretations of data may be influenced by my background. While I try to stay neutral and open to all possible outcomes of the research, the lens through which I collect and analyze data has been

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colored by my personal experiences and qualitative research is by definition interpretive.

**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 (Shadish, Cook, & Campbell, 2002). 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. The second class was to be chosen to be the control group. In order to determine the effects of five particular teacher-led demonstrations designed to target alternative conceptions about heat transfer, the third class received the ETK treatment with these special demonstrations that will be described in detail in Chapter 4. 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 special 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 with special demonstrations. These demonstrations will be described in detail in Chapter 4.

Phase 3: Preliminary Observations and Interview with Teacher Participant

Two weeks prior to the start of the heat transfer unit in the dissertation study, the researcher began observing all three classes. One purpose of conducting these preliminary observations was to document the typical interactions in each classroom, establishing a baseline for typical behavior of individual students and the typical teaching style of the teacher. When the students were studying heat transfer in the experimental or control groups, it was possible to note differences in behavior or attitudes. This observation period also allowed the students to become familiar with the presence of an observer taking notes and recording classroom behaviors and vocal exchanges. It also gave the researcher the opportunity to test out the video and audio recording devices to make sure they captured the intended behaviors and vocalizations. The researcher took
field notes that focused on the teacher’s choice of activities, her interactions with the students, her level of questioning, her classroom management, and her overall demeanor. The researcher also took field notes on how individual students participated in class, how they cooperated with one another, how they engaged in the science content, and how the overall class dynamic played out.

During this two week observation period, the teacher participant was interviewed with the Entrance Interview protocol in Appendix H. As stated previously, the purpose for the teacher entrance interview was to establish a profile for how the teacher viewed her teaching, determine whether she was familiar with inquiry-based teaching, what her goals were for teaching heat transfer, and what her thoughts and feelings were about teaching science through engineering design. Also, her lesson plans, assessments, assignments, and activities/labs for the heat transfer unit were collected for analysis to make sure that the three groups would have equivalent exposure to opportunities to learn about heat transfer. Through the process of analytic induction, the observation notes and artifacts were coded, and as codes were collapsed, tentative assertions were created. These assertions were tested and used to create a profile of the teacher’s philosophy of science teaching and specifically how she taught all three classes during the heat transfer unit.

Phase 4: Pretests, Entrance Interviews, Observations, Posttests, and Exit Interviews

The purpose of this phase was to answer the research questions and determine whether learning science through engineering design activities made any difference in
student conceptual understanding or student attitudes toward and understandings about engineering.

In order to collect the data necessary for a description of students’ intellectual and physical responses to design-based science activities, the teacher taught the Control class in her usual manner, using the activities and lessons she typically incorporated. The experimental classes were presented with the heat transfer ETK curriculum. Students in the control and treatment groups spent the same amount of time studying the science concepts, and they had the same learning objectives based on the state and national standards.

Students in three eighth-grade classes participated in this study. All students in each class participated. Students in all three groups were administered the Heat Transfer Evaluation and the Attitudes toward Engineering survey two weeks prior to and immediately after the intervention (Appendices F & H). While students wrote their names on their assessments, these names were cut away and replaced with a code known only by the researcher. The key for this code was kept in a locked file and was destroyed after the conclusion of data collection. These tests served as one method of measuring achievement and attitude changes, but more importantly, as prompts for later interview questions.

Semi-structured entrance interviews with participating students took place during the 2 week period leading up to the intervention (Appendix I). The purpose of the entrance interviews was to find out what students’ conceptions of heat transfer were,
explore in more depth some of their responses to questions on the content test, ask them a content-based question to see if they could demonstrate understanding through discourse, and give them a performance assessment of understandings about heat transfer. Also, students were asked if they liked science, and if they knew any engineers, or knew what engineers do. Out of 21 students in the ETK class, 8 participated in both entrance and exit interviews. For the exit interviews, 2 more participated for a total of 10 students. Out of 27 students in the Control class, 10 participated in both entrance and exit interviews. Out of 23 students in the ETK+D class, 11 participated in an entrance interview and 10 students participated in an exit interview, for a total of 9 students participating in both entrance and exit interviews in the ETK+D class. Entrance interviews lasted from 13 to 25 minutes with a mean of 16 minutes for the ETK class, 17 minutes for the Control class, and 19 minutes for the ETK+D class. To facilitate timely interviews, research assistants were trained to help conduct entrance interviews. Training consisted of reviewing the qualities of effective interviewing, and practice sessions between interviewers. Interviewing did not begin until the researcher was confident in the skills of the interviewers, and recordings were reviewed daily for any formative feedback necessary. Students volunteered for the opportunity to interview with the researcher, but in order to check for a biased sample of volunteers and eliminate potential participants, students’ HTE pretests were compared with a one-way ANOVA and shown to be statistically equivalent ($p = .715$) with means of 4.38 for the ETK class, 4.9 for the Control class, and 4.1 for the ETK+D class. Each sample equally represented a distribution of students who scored high, middle, and low on the heat transfer evaluation
During the dissertation study, the researcher audio taped and videotaped the classroom settings of both the control and treatment classes in order to hear and see actions and vocalizations out of sight or earshot. The teacher wore a lavaliere microphone, and in addition, classroom audio was mixed in with the on-board microphone of a Canon XL1 digital video recorder. Additionally, audio and video records helped with the daily transcription and interpretation of observation notes. Classroom observation field notes were used to help analyze the conversations that took place between the teacher and her students, and students with each other, particularly as they engaged in activities designed to help them understand the science concepts. Wireless microphones with digital voice recorders picking up the audio were given to different student groups during the intervention in order to record simultaneous conversations for analysis when groups were working on either the design project or when groups in the control class were working on non-design projects. Particular attention was be paid to how the students’ behaviors and attitudes changed over time, in particular their conceptions of heat transfer, their use of scientific knowledge in the design of the ice-penguin dwelling, and their correct use of scientific terms and concepts. Vygotsky (1978) theorized that in studying anything, the process of change must be examined. “To study something historically means to study it in the process of change; that is the dialectical method’s basic demand... for it is only in movement that the body shows what it is” (pp. 64-65).
Three treatments

In order to test the effects of engineering design activities and special demonstrations targeted at 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 narrated by Bill Nye (Nye, 1996), which contained other visual imagery and demonstrations, and the teacher showed them demonstrations she had used the year before in her typical instruction. The entire ETK curriculum used in this study, Save the Penguins, complete with the demonstrations, is provided in Appendix A. These treatment groups are discussed in greater detail in the following section.

Treatment Groups

In this section, the three instructional treatments are described in detail. Each group was treated as equivalently as possible in terms of the learning objectives and opportunities to accomplish them, time spent by students on the topic of heat transfer and thermal energy, homework assignments, and daily journal exercises. The researcher observed all three classes for the duration of the interventions. During the 2 week interventions which encompassed 6 class periods of 83 minutes each, students in each group were learning about heat transfer and thermal energy in different ways. The
researcher took notes on what questions the teacher was asking, what explanations the students were providing, what conversations students were having during group exercises, and what kinds of explanations students provided during their journaling exercises. From this data, the assertion could be made that students' scientific conceptions about heat were developing in different ways and to different degrees.

*The Save the Penguins ETK Class*

The first class was taught with the *Save the Penguins* ETK. The broad context for the *Save the Penguins* ETK was global warming. Students discussed that the energy used to heat and cool their homes and schools comes from power plants, most of which use fossil fuels to convert chemical energy to electrical energy. The burning of fossil fuels has been linked to increased levels of carbon dioxide in the atmosphere, which in turn has been linked to increases in global temperature. This change in temperature has had widespread effects upon life on Earth. Many species of penguins live in the southern hemisphere, primarily on the icy continent of Antarctica. As the Earth warms and ice melts, penguins lose habitat. Global warming has been directly linked to the population decline of the emperor penguins (Jenouvrier, Caswell, Barbraud, Holland, Stroeve, & Weimerskirch, 2009). Energy efficient houses that minimize unnecessary heat transfer draw less electricity from the fossil fuel burning power plants and do not contribute as much to global warming. Therefore, students realized that better engineered houses that use less energy for heating and cooling might have a positive effect on the lives of penguins. They learned about the positive impact engineers can have on the living creatures of the world.
The Save the Penguins ETK was a 6 day unit that included an introduction to engineering, an introduction to the environmental conditions affecting penguins, an introduction to the science of heat transfer and thermal energy, then an introduction to the design-build-test-redesign iterative engineering design process. Students worked in small groups within the constraints of time, space, and budget to construct a small dwelling for a penguin-shaped ice cube. The dwellings were placed in a test oven, and as the dwellings were exposed to heat transfer by conduction, convection, and radiation, students saw firsthand how heat transferred. The six day schedule was as follows:

Day 1
Homework review
Introductory PowerPoint
Discussion about engineering
Introduction to storyboard

Day 2
Homework check
Journal exercise
Discussion about heat
Three demonstrations

Day 3
Homework check
Journal exercise
Bill Nye video
Introduction to the design challenge
Students test materials

Day 4
Planner check
Journal exercise
Testing materials
Initial construction

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Day 5
Construction and testing of first dwelling design

Day 6
Sharing results
Construction and testing of second dwelling design
Posttests and unit test

Prior to designing and constructing the dwelling, students worked in their small groups to test the materials that were available to them. They had available construction materials like felt, Mylar, foam, wooden sticks, construction paper, cotton balls, and bubble wrap. They used heat lamps and thermometers at test stations around the room to conduct experiments and evaluate the properties of the different materials. The results of these experiments were shared among the groups. With a fixed budget to purchase supplies, students made decisions judiciously.

After the first test of the dwellings in the test oven, students were given an additional day to redesign. The results from the first iteration of the design were shared between groups, and students made re-design decisions based on their own successes and failures, and those of their peers. Success was determined by measuring the mass of the remaining penguin-shaped ice cube. The ice cube had a mass of 10 grams initially, and after exposure to heat transfer in the test oven for 20 minutes, most ice cubes lost half their mass due to melting.

Student groups kept a record of their design decisions and experimental results on a storyboard. The storyboard told the story of their design from start to finish. Student groups shared their storyboards in pin-up sessions during the unit so that the effort was
truly collaborative.

Students in all classes were given the same homework assignments, completed the same journal entries each day at the beginning of class, and took the same teacher-created test at the end of the unit.

The Control Class

Students in the Control class learned the same scientific concepts of thermal energy and heat transfer as students in the two engineering design classes. While students in all three classes had the same homework assignments and journal activities at the beginning of class, and the same unit test at the end, for this class the teacher used the lesson plans, activities, and materials that she used the year before. The six day schedule was as follows:

Day 1
Homework review
PowerPoint on thermal energy
Bill Nye video
Make flip chart for definitions

Day 2
Homework check
Journal exercise
Three demonstrations
Phase change laboratory

Day 3
Homework check
Journal exercise
Introduction to Excellent Energy project
Students research at computers
Day 4
Planner check
Journal exercise
Work on poster for Excellent Energy project

Day 5
ExploreLearning activity at computers

Day 6
Posttests and unit test

The teacher started with a PowerPoint lecture/discussion about temperature, thermal energy, and heat transfer.

She described the three methods of heat transfer and discussed examples of each with students.

Students illustrated and defined key definitions and terms this first day on a flip chart. Then, students watched a 26 minute Bill Nye science video on the topic of heat. This video contained several demonstrations performed by Nye. One compared thermal energy and temperature between a match and an ice sculpture. Nye tried to melt the sculpture with the match, and explained that even though the match had a higher temperature, the large ice sculpture contained more thermal energy and thus could not be fully melted by it. He also demonstrated making a paper spiral on a string. When placed over a toaster, the spiral began to spin. Nye explained that as hot air rose, it pushed on the spiral and spun it around.

The teacher performed several demonstrations to illustrate heat transfer and
thermal energy. She dropped food coloring into a beaker of cold water and a beaker of hot water to illustrate the kinetic energy possessed by hot water. She placed a balloon in the freezer while one stayed in the classroom to demonstrate thermal contraction. She had students observe and comment on the temperature change in two beakers: a small beaker of ice cubes placed in a larger beaker of boiling water. On the second day of the unit, students performed a phase change laboratory. They observed and took the temperature every minute of ice cubes in a beaker on a hot plate as the ice cubes melted and then boiled. They plotted these data points on a graph and answered questions on a lab sheet.

Students spent two class periods working on a project called Excellent Energy in pairs. Students were challenged to research a product designed to prevent heat transfer, and then create a colorful brochure to sell and market that product. Students were tasked with thinking about and documenting how this material might prevent the three types of heat transfer. The product could be clothing or a building material. One pair researched wool, another researched windows that changed with the amount of sunlight, and another researched radiant barriers installed in attics. With 27 students in this class, there were 13 different products and brochures created. Depending on the product they chose, students could have been exposed to some concepts about engineering.

This was an independent project to some degree, with the teacher only providing tangential support. Students did not share their brochures prior to being collected.

Students spent another class period using a computer simulation called, “Heat
Transfer by Conduction” from the educational website, ExploreLearning⁶. Students worked in pairs at a computer in the computer lab. The teacher gave each student a set of directions and worksheet on which to answer questions. The simulation involved two beakers of water with a piece of metal connecting them. One beaker contained water at 95°C and the other contained water at 5°C. See Figure 6 for a screenshot of this simulation.

![Simulation Diagram]

*Figure 6. ExploreLearning screenshot from the conduction simulation. Used with permission.*

The last day of the unit was spent reviewing for and taking the unit test and the posttests for this study.

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⁶ ExploreLearning, [http://www.explorelearning.com](http://www.explorelearning.com), is a subscription service that the county provided the teachers in the district.
The Save the Penguins ETK + Demonstrations Class

The third class used the Save the Penguins curriculum in exactly the same way as the first class, except that they did not watch the Bill Nye video, they did not watch the food coloring in water demonstration, the balloons demonstration, or the beaker of ice cubes melting in a beaker of hot water demonstration. They had the same introduction to engineering, the same context of global warming and penguins perishing, and the same design challenge to build a structure to keep a penguin-shaped ice cube from melting. Instead of the video demonstrations and typical demonstrations, they were exposed to five special demonstrations designed to target research-based alternative conceptions students typically hold about heat and energy. The six day schedule of events was as follows:

Day 1
Homework review
Introductory PowerPoint
Discussion about engineering
The cans demonstration

Day 2
Homework check
Journal exercise
Discussion about heat
Introduction to storyboard
The trays and spoons demonstrations

Day 3
Homework check
Journal exercise
The house and Mylar demonstrations
Introduction to the design challenge
Students test materials
Day 4
Homework review
Journal exercise
Testing materials
Initial construction

Day 5
Construction and testing of first dwelling design

Day 6
Construction and testing of second dwelling design
Posttests and unit test

The overall purpose for the special demonstrations was to engage students in cognitive dissonance and encourage conceptual change. Cognitive dissonance is one of several research-based approaches that can be used for promoting conceptual change. First, students are made aware of their conceptions, and then they are presented with a discrepant event which challenges their existing ideas (Nussbaum & Novick, 1982; Scott, Asoko, & Driver, 1991). Students in the ETK+D class participated in five teacher-led demonstrations about heat transfer. They were designed to target research-based alternative conceptions typically held by middle school science students. Entrance interviews and pretests by students in this study reflected these same research-based alternative conceptions. Also, the demonstrations were designed to help the students learn scientific concepts which might be beyond the students’ reach when not assisted (Wood, Bruner, & Ross, 1976). In all, these demonstrations consumed one class period out of the six class periods in the study.
The 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 7). 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.

Figure 7. The cans demonstration.

This demonstration took 20 minutes.

The 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 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. The trays demonstration took 10 minutes.

*The 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, because that is what they feel. For the spoons demonstration, students were given a sterling silver spoon and a plastic spoon to hold (Figure 8). An ice cube was placed in each spoon, and students were asked to predict which ice cube would stay frozen the longest.

*Figure 8. The spoons demonstration.*
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.

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 9). A heat lamp was shining on the roof and thermometers were measuring the temperature of the air in the attic and the air in the first “floor.” Mylar was not draped over the roof so the temperature in the “attic” quickly got very hot.

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.
Figure 9. The house demonstration with Mylar draped over the roof

She asked students to predict the temperature changes, and asked them to explain what was going on. Students also discussed why the attic of the house was so much hotter than the first floor. This demonstration gave students an internal mental image of hot air rising and cooler air sinking in the house. The house demonstration took 20 minutes.

The 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 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.

**Discourse Analysis**

Vygotsky (1978) considered discourse to be a tool at the heart of teaching and learning. There are a broad range of conversational styles in a middle school classroom. The teacher may elicit the standard triadic dialogue, Initiation-Response-Evaluation (IRE), in which she asks questions, a student responds, and the response gets evaluated. This is typical of traditional teaching (Chin, 2006). It can have merit if the teacher uses IRE as an opportunity to scaffold students’ knowledge and guide their ideas. However, there are many other styles in which the student takes on a greater role in initiation, response, or evaluation. The teacher can take on the role of orchestrator in this student-centered discourse.

Vygotsky (1978) theorized that conceptual knowledge first appears in the social setting, and then becomes integrated inside the learner. The teacher can guide students’ discourse to facilitate this transformation in a variety of ways and at a variety of levels of teacher control. Authoritative discourse focuses on information transmission, and student involvement often consists of single utterances. However, dialogic discourse opens up the floor to debate and discussion as students share their ideas (Chin, 2006).
In the dissertation study, in addition to class discussions, group conversations between students during independent work time were analyzed. Group dynamics were recorded to document how well group members interacted with each other, whether particular students dominated the decisions and whether particular students were ignored and acted as if they were just watching. The researcher took notes about how often students engaged in off-task behaviors unrelated to the science objectives, noting type, cause, time intervals and durations. She recorded the questions students asked of each other and of the teacher, and recorded the type of scaffolding the teacher provided. The evolution of the students’ ideas about heat, temperature, and heat transfer was especially noted. Differences between teacher-student and student-student discourse in the control and the experimental groups were noted, with an emphasis on the degree to which discourse furthered conceptual understanding. When students were talking together in groups, the difference between discourse about “how to” solve a problem was differentiated from discourse about “why” certain solutions were chosen (Hogan, Nastasi, & Pressley, 1999). Patterns of all types of verbal interactions were noted and analyzed. As with Hogan et al., macrocoding included categories such as scientific talk, procedural talk, and off-topic talk. Microcoding included categories such as presenting ideas, presenting information, summarizing, repeating, evaluating one’s own idea, evaluating another’s idea, reflections about understanding, reflections about not understanding, requesting information, and so forth. Open coding allowed codes to emerge from the data. The patterns of verbal interactions were compared between the experimental and control classrooms.
Classroom observations of student behaviors and affects, teacher behaviors and affects, and the convergence of the two, and analysis of the types of discourse present in the classroom are integral to the methods of this study, as pre and post tests alone do not tell the complete story about how students may engage in design-based science curricula. Field notes were transcribed, audio tapes of group discussions were transcribed, and video tapes of whole-classroom instruction served as a way to validate observer field notes. Student artifacts were collected for analysis of evidence of cognitive change over time, and also used as prompts during the student exit interviews. Any student work, whether classwork or homework, was collected from the students. Naturally, their names were covered and replaced with a code, and the assignments were photo copied for use as part of the analysis of cognitive change. Finally, observations between the experimental and control classes were compared daily to judge whether students in each class were having equal opportunities to learn the science content. The primary rubric for that judgment was the percentage of time spent per class period on relevant science content, and also, any science activities or discussions were mapped to the learning objectives to assure that students in each class covered the required objectives. Discrepancies were noted and attended to by the researcher and teacher in discussions following each day of the intervention.

After the Intervention

All students in each class took posttests immediately after the heat transfer unit. All students in the study took the Heat Transfer Evaluation, the Attitudes towards
Engineering Survey, and a teacher-created assessment as posttests.

Semi-structured exit interviews with participating students in all classes took place as soon as possible after the posttests, not exceeding one week. See Appendix J for the student exit interview protocol. The purpose of the exit interviews was to find out if students understood the questions on the posttests, find out what they thought they learned about heat transfer, explore in more depth some of their responses to questions on the content test, determine their attitudes toward science and engineering, and finally, if they were in the experimental group, find out their rationale for design decisions made about their penguin dwelling. Students were asked to explain their reasoning for some of the answers they chose. Particular attention was given to any references to science activities conducted during the heat transfer unit, whether design-related or not. The exit interview was also used as a method of dynamic assessment. While static measures like pencil and paper tests describe an individual’s actual level of development, dynamic measures reveal a child’s potential, Vygotsky’s Zone of Proximal Development. The interviewer flexibly interacted with the students in an individualized manner, and using reminders or prompts when necessary. This sort of scaffolding was noted, as were the ways in which the students responded to prompts. The social constructivist framework supports dynamic assessment practices mediated or guided by another (Palincsar, 1998).

The researcher looked for any differences between answers given by students in the control and experimental groups. All the questions helped the researcher answer research question #3, “What are ways in which an engineering design challenge changes students’ conceptions of heat transfer?” The interviews were audio recorded and
transcribed for analysis. Students were informed that their participation was voluntary, and that their responses would be kept confidential. In the transcription, their name was not used, only a code known only to the researcher. The original tape recordings were destroyed after transcription and analysis. Students were provided a small gift for participating in each interview. Interviews took place during lunch, during the school’s study hall period, and before and after school. For the exit interviews, ten students from each class participated. Each interview lasted from 6 to 27 minutes with a mean of 18 minutes in the ETK class, 13 minutes in the Control class, and 15 minutes in the ETK+D class. The reason interviews were shorter in the Control class was that questions about the design were not included. Interviews did not take time away from science instruction nor did they disrupt the schedule of the school day.

*Phase 5: Exit Interview with Teacher Participant*

Student data and classroom observations aside, a great deal of information came from feedback from the teacher participant. She knew her students best and could share a great deal of insight with the researcher regarding her perception of how the intervention affected her students. The purpose of this semi-structured exit interview was to probe the teacher’s feelings and attitudes about teaching with design-based activities, her attitude toward inquiry-based science teaching, and her perceptions of how her students responded to the intervention and the typical instructional techniques. This interview was conducted by the researcher, and took place during the week after the intervention concluded. It was tape recorded and transcribed for analysis. See Appendix K for the teacher exit interview protocol.
Data Analysis

This research is described as mixed-methods, where qualitative and quantitative methods are used to both collect and analyze data. The purpose of this phase of the research was to find enough compelling evidence to answer the research questions. Qualitative and quantitative data were collected concurrently, but analysis took place in two phases. Qualitative data was analyzed in an ongoing manner so that the researcher could explore emerging theories and trends as the study progressed. This in turn, gave the data collection methods direction and increased focus to narrow the study as time went by (Bogdan & Biklen, 1992). After qualitative data were collected and analyzed, these results were compared to and mixed with the results of the quantitative data analysis. Since this is a small-scale case study of 1 teacher and three classes of students, the confidence of the quantitative results is diminished, and the qualitative data analysis had priority over the quantitative. Analysis of the mixed data was carried out in the interpretive framework of analytic induction (Bogdan & Biklen, 1992; Erickson, 1986).

Interpretive methods are not used to merely describe, but to interpret the actions seen in the situation. The technique of recording observations is not the same as the method of interpreting them because different observers can interpret the same events quite differently. Interpretive research sees classrooms as “socially and culturally organized environments”, sees that teaching is only one aspect of the learning environment, and sees that teachers and learners can have very different perspectives on meaning. Interpretive research is used to closely analyze details with a focus on both the everyday context and the “wider societal context” (Erickson, 1986).
In qualitative research, the researcher is the instrument. A reflective journal was used throughout the study to record the researcher’s thoughts and processes. The researcher not only made observations as a “fly on the wall”, but walked around the room, listening to and writing down various conversations as students designed and built their devices. To avoid becoming part of the treatment, the researcher referred all questions to the teacher and spent the same amount of time closely observing student groups in both classes.

Fieldwork consists of long-term involvement, careful recording and collection of artifacts, analysis, and reporting (Erickson, 1986). Reporting can take the form of quotes, vignettes, charts, tables, and descriptive statistics. However, interpretive fieldwork includes reflection in an attempt to find the significance of events from various points of view. Interpretive methods are appropriate when specifics are needed, when meaning is needed, when comparisons are needed, and when theories are needed to elucidate data or experiments. Questions one might ask are: what is going on, what does it mean to the people involved, how are the people involved connected, how do the goings-on relate to the big picture, and how do the goings-on relate to other activities or settings?

Interpretive research is all about figuring out how local and non-local influences affect people’s behavior. Interpretive researchers search for concrete universals by studying something in detail then comparing it to other cases which are also studied in detail.

Analysis of data was on-going as the researcher collected data from the
classrooms, transcribed and reflected upon it, recorded emerging patterns and themes in an analytic journal, and created tentative assertions. The researcher used the qualitative analysis software, NVivo, to help code, organize, and analyzed the data. Data consisted of student interview transcripts, teacher interview transcripts, transcripts of video and audio footage in the classroom, designed artifacts, assignments completed by students, and field notes taken by the researcher. In addition to data from all student participants, descriptive profiles were developed for each student who participated in both entrance and exit interviews. These profiles described the student's overall affect, their level of participation in the activities, their professed attitudes toward science and engineering, their conceptions about heat transfer, and whether their conceptions changed over the course of the intervention. Entrance and exit interviews for matched participants were compared to discern any changes in student conceptions of heat transfer, attitudes toward and understandings of engineering. The interview responses were also compared to classroom dialog and responses to homework and other assignments. Specifically, the researcher looked at how these students' conceptions of heat transfer, whether scientific or not, changed in the process of teacher-student dialog, student-student dialog, and student centered activities, whether design-based activities or other types of activities presented by the teacher. The researcher looked for change over time in terms of how students expressed their conceptions of heat.

Entrance and exit interviews with the teacher were compared and combined to ascertain an overall picture of how the teacher perceived the differences between the experimental and control groups. Classroom discourse during the intervention was
analyzed and coded as the discourse was transcribed from tape. Classroom behaviors by both students and teacher were coded and analyzed as the behaviors were viewed on video tape, and as field notes were transcribed. The design storyboards from each group were collected and analyzed for evidence of conceptual change. The final penguin dwellings from each student group in the experimental class were collected and analyzed for scientific use of materials. The data were searched and assigned codes in vivo, and after preliminary codes were developed, the data were searched again with a complete set of codes. Preliminary assertions were developed and the data corpus was searched for confirming and disconfirming evidence as assertions were fine-tuned.

After the qualitative data were analyzed, the quantitative data was examined in detail. The quantitative data provided for confirmation, cross-validation, or corroboration of the findings from the qualitative analysis (Creswell, 2003). Descriptive statistics were computed and analyzed for both pre- and posttest instruments. Gall, Gall, & Borg (2003) suggest that in order to reduce the probability of error, when inferential statistics are used to compare two samples, there should be at least 15 participants in each group. Since an adequate participation rate was met for each class, pre- and posttest data were analyzed to look for differences between the control and experimental groups, any possible differences between gender, interactions, and differences across time within each treatment group. This is called a pretest-posttest control group design (Shadish, Cook, & Campbell, 2002), and the researcher acknowledges that the following procedures reflect a quasi-experimental situation since students could not be randomly assigned to the three treatment groups.
The content-based Heat Transfer Evaluation is a 12-question multiple choice 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.

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. The Likert-scale choices on the surveys, while they are ordinal, are symmetrical. Since the survey measured one construct (attitude), a mean was computed for each of the items for each participant. Jaccard and Wan (1996) summarize, “for many statistical tests, rather severe departures (from intervalness) do not seem to affect Type I and Type II errors dramatically” (p.4).

Statistical tests were run with the software program Statistical Package for the Social Sciences (SPSS) to test for differences between groups and changes over time with an alpha level of 0.05. This particular study has three treatments, two assessments, and two times.

Triangulation of all these varied sources of data were important in creating valid assertions about how this particular design-based science activity and the targeted demonstrations affected students’ conceptions about thermal energy and heat transfer, and attitudes toward and understanding about engineering. Assertions were also based on the role that social climate had on learning and attitude, the role of artifact-mediated group work, the role of the teacher in scaffolding student learning, and the role of student
teams working in cooperation with each other.

**Linking Methods with Theoretical Framework**

The focus of the methods in this study is conceptual change. The question is how engineering design can facilitate conceptual change in the area of thermal energy and heat transfer, but also change in attitudes towards and understandings about engineering. Social constructivism and conceptual change theory stress that students are not blank slates, that they come to science class with preconceptions, and that through teacher facilitation and social collaboration these conceptions can be challenged and modified over time (Posner et al., 1982).

The intervention was designed to take advantage of the ideas of both social constructivism and conceptual change. Students were working in small, social groups under the guidance of a teacher, and collaborating both within groups and between groups. They were testing their ideas through multiple iterations of design and multiple experiments with materials. They were sharing their new-found knowledge through storyboards displayed for all to see, and through brief presentations. The teacher acted as the “more knowledgeable other” scaffolding their learning through appropriate coaching techniques. The researcher determined students’ alternative conceptions prior to the intervention through pretests and interviews, and shared these in aggregate with the teacher. The results of this phase informed the teacher’s methods of helping students see the incongruity of their ideas and the logic of more scientific ones.

Social constructivism is best suited to research focused on questions of “how” as
opposed to questions of "if" (Ferguson, 2007). The research questions for this study asked how students construct knowledge about thermal energy and heat transfer and attitudes toward and understandings about engineering through highly-engaging design-based activities. Through interviews and discourse analysis, the researcher focused on seeing things from the participants' points of view, furthering the quest to discern "how." Guba and Lincoln (2005) stress that constructivist research methodologies should be both hermeneutic and dialectic. Interpretive and logical methods were planned through the addition of interviews, observations, and discourse analysis to the traditional quantitative pre- and posttests. Quantitative research alone would not have met the dialectical criterion.

The artifacts that students created demonstrated their knowledge, and discussions about the artifacts helped "illuminate the knowledge that is constructed in the mind of the learner, and thereby align with constructivism as a research lens" (Ferguson, 2007, p. 34). Interview questions about the artifacts also contributed to the dialectical nature of this study.

Data analysis followed the philosophy of social constructivism as well. Through the interpretive act of analytic induction, theories emerged from the data and assertions were created in order to answer the research questions.
CHAPTER 4: RESULTS

Introduction

The purpose of this investigation was to better understand: a) how middle school students could learn about thermal energy and heat transfer at a deep conceptual level and b) develop positive attitudes and better understandings about engineering. The investigation was enacted through an engineering design challenge on the topic of heat transfer. The study focused on identifying the conceptions students had about heat transfer and engineering, and documenting how those conceptions changed throughout the study. By comparing the qualitative and quantitative results from three different treatment groups, inferences could be made about how engineering design may have affected science concept understanding, and how alternative conceptions may have been altered through specifically designed demonstrations that linked the engineering design activities with the heat transfer content. The research questions targeted in this study were:

1) How might students’ conceptions about thermal energy and heat transfer differ before, during, and after engineering design-based instruction and typical instruction on the topics of thermal energy and heat transfer?

2) How might students’ conceptions about and attitudes toward engineering differ before, during, and after learning heat transfer and thermal energy through an engineering design challenge?
3) How might an engineering design challenge specifically change students’ conceptions of thermal energy and heat transfer?

This chapter is organized into four sections. The first section provides an overview of the teacher, her classroom, and her classes. The second section describes the heat transfer concepts possessed by students in each class prior to, during, and after the interventions and provides assertions for research question 1. The third section describes the conceptions students in each class had about engineering, and their attitudes toward engineering prior to, during, and after the interventions, and provides assertions for research question 2. The third section attempts to answer research question 3, and describes specifically how the engineering design challenge used in two of the classes may have impacted student’s conceptions of heat transfer and thermal energy.

The Teacher, her Classroom, and her Classes

Miss Smith taught six eighth-grade science classes. She taught three advanced-level 83 minute classes one day and three standard-level 83 minute classes the next day. This alternating pattern continued throughout the school year. Miss Smith’s room was neat and tidy. There were lab stations around the room equipped with sinks. The black counters were clean with no cracks or chips. There were wooden cabinets up and down, half having glass doors. Handmade musical instruments sat on top of the cabinets. Supplies were well organized. A shelf by the door had plastic bins of art supplies and calculators, all labeled. The top of this shelf held a three-hole punch, lotion, hand sanitizer, and an air freshener. To the right of the shelf was a rolling cart with stackable inboxes, tape, a stapler, and electric pencil sharpener, and another three-hole punch.
Handouts were neatly stacked on the cart. There was a small library of books—many of them dictionaries and encyclopedias—and some dog-eared science books. There was a digital projector mounted to the ceiling and an Apple computer on the teacher’s desk with a computer printer located on a bookshelf next to her desk.

Students sat at science tables with black tops and oak legs. They were very clean and nice looking, not more than a couple years old. The white board in the front of the room was very well organized into sections. On the left was a homework chart which projected into the following week. Reminders were written on the board. Many colors of ink were used to make it an attractive display. The walls were bare white painted cinderblock, and the classroom rules hung on the front wall. “In this classroom we will behave in a manner that will not cause a problem for others and ourselves”. There were science process posters on cabinet fronts labeled: observe, hypothesize, infer, follow directions, experiment, sequence, measure, classify, create, and graph.

There was a large window in the back of the room with formal blue long dark curtains hanging to each side and a vase of bright fabric flowers on the window sill. The walls look freshly painted. The linoleum floor had a pattern of light and dark tiles, mostly light. In summary, the classroom was bright and clean and well-organized. The teacher obviously put great thought into what supplies students might need, and arranged the classroom for their comfort.

The students in the advanced classes were generally very well behaved. They rarely made disruptions, rarely left to go to the bathroom, only occasionally got up to
sharpen a pencil, and infrequently disrupted the flow of the lesson. Students got along with each other. No student seemed to be left out. Even the quiet or eccentric students had friends to sit with and work with in groups.

The teacher, Miss Smith, was in her late 20s but could have passed for a teenager if it were not for her demeanor and dress. She was attractive and well dressed, with short brown hair she usually wore pinned up with a barrette. Miss Smith wore high heels nearly every day, whether she wore a skirt, dress, or dress slacks. She did this, she said, to give her a height advantage over some of the more mature eighth-grade boys. She was very well organized with her daily classroom rituals. Every week began with a planner check. Every day began with a homework check, an agenda projected onto the whiteboard, and a journal activity. Every student had a binder for science classwork and homework, while textbooks generally stayed in the classroom and were retrieved when necessary. Every class period ended with a homework assignment, which was then checked the next time class met. Miss Smith’s philosophy of science teaching was to give students a solid background in the basic facts first, then do some demonstrations to get them hooked, then assign a formal lab or project so they “really get into the meat of the topic.” She felt that the basic facts were important— even if a bit dry— so that students would have the correct vocabulary for the unit of study. She typically used PowerPoint to deliver this introductory material.

Heat Transfer Conceptions

Research Question #1: How might students’ conceptions about thermal energy
and heat transfer differ before, during, and after engineering design-based instruction and typical instruction on the topics of thermal energy and heat transfer?

Students' conceptions about thermal energy and heat transfer are not typically scientific. Many studies have shown that children and adults alike have many alternative conceptions about heat (Albert, 1978; Clough & Driver, 1985; Erickson, 1979; Erickson, 1980; Erickson, 1985; Paik et al., 2007). This research question asks whether students' conceptions about heat were similar across treatment groups prior to the intervention, then looks at how these conceptions may have changed for each class. Results from this question are presented as assertions with supporting evidence from quantitative test results, interviews prior to and after instruction, and classroom observations and assignments during the interventions.

Assertion 1: Students' conceptions of heat transfer were similar across all three groups prior to instruction.

Prior to the intervention, students from all three classes were administered the Heat Transfer Evaluation (HTE) (Appendix F). Scores from the three classes were compared to ascertain whether students could be treated as if they were from the same population. A one-way ANOVA demonstrated that the three classes of students scored statistically the same on their heat transfer evaluation pretests, so they were considered to be equivalent groups.

HTE Pretests

Students in the ETK class, \( n = 21 \), obtained a mean score of 4.33 \((SD=1.83)\) out of 12 points on the HTE pretest. Students in the Control class, \( n = 27 \) students, obtained a
mean score of 4.63 ($SD=1.64$) out of 12 points. Students in the ETK+D class, $n=23$ students, obtained a mean score of 4.09 ($SD=1.81$) out of 12 points. These scores were slightly better than chance. With four answer choices per question, it was expected that a student with no scientific conceptions of heat transfer would score a 3.0 out of 12 points. Inferential statistics were used to determine if the three classes were statistically equivalent in terms of heat transfer knowledge. A one-way ANOVA was performed, resulting in $F(2,68) = 0.601$, $p = .551$. Levene’s test was not significant ($p = .763$) indicating that the variances were not significantly different between classes. The distribution in the ETK class was moderately skewed (skewness = .432) and had a moderate kurtosis (kurtosis = .484), but the ANOVA is robust to slight deviations from normality when the sample size is large enough and there are no outliers (Field, 2005; Tabachnick & Fidell, 2001). An examination of the z-values demonstrated that outliers did not exist (no absolute values greater than 3.29). The effect size was computed to be $r = .09$. Figure 10 illustrates the box plots representing the distribution of scores in each class. The range, median, and first and third quartiles are easily depicted.

Just to be safe, a nonparametric Kruskal-Wallis test was used to determine if groups were indeed equivalent considering the non-normal distribution in one class. The test statistic $H(2) = .686$, with $p = .709$ so the groups were again determined to be equivalent in terms of heat transfer knowledge.
Figure 10. Box plots representing HTE pretests for each class.

Table 2 illustrates the percentage of students from each class who answered each question on the HTE pretest with the correct answer. Following Table 2 is a description of how students performed on the HTE pretest compared to the major learning objectives planned for all three classes in the study. The standards-based learning objectives (AAAS, 1993; NRC, 1996) used to teach students were:

1. Heat is thermal energy in motion.
2. Heat is transferred from a warmer object to a cooler object.
3. Insulation slows down the rate of heat transfer.
4. Heat can be transferred across space through radiation.
5. Conduction is the transfer of heat through contact.
6. Fluids in motion transfer heat through convection.

7. Heat and temperature are not the same.

Appendix C has a complete list of the standards used to guide the intervention, while Appendix F contains the Heat Transfer Evaluation instrument used pre- and posttest.

<table>
<thead>
<tr>
<th>Question</th>
<th>ETK Class ((n = 27))</th>
<th>Control Class ((n = 21))</th>
<th>ETK+D Class ((n = 23))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24%</td>
<td>11%</td>
<td>13%</td>
</tr>
<tr>
<td>2</td>
<td>38%</td>
<td>22%</td>
<td>9%</td>
</tr>
<tr>
<td>3</td>
<td>10%</td>
<td>7%</td>
<td>0%</td>
</tr>
<tr>
<td>4</td>
<td>33%</td>
<td>48%</td>
<td>43%</td>
</tr>
<tr>
<td>5</td>
<td>14%</td>
<td>15%</td>
<td>13%</td>
</tr>
<tr>
<td>6</td>
<td>71%</td>
<td>89%</td>
<td>61%</td>
</tr>
<tr>
<td>7</td>
<td>90%</td>
<td>93%</td>
<td>83%</td>
</tr>
<tr>
<td>8</td>
<td>48%</td>
<td>59%</td>
<td>52%</td>
</tr>
<tr>
<td>9</td>
<td>14%</td>
<td>11%</td>
<td>22%</td>
</tr>
<tr>
<td>10</td>
<td>29%</td>
<td>30%</td>
<td>35%</td>
</tr>
<tr>
<td>11</td>
<td>5%</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>12</td>
<td>57%</td>
<td>74%</td>
<td>74%</td>
</tr>
<tr>
<td>Overall</td>
<td>36%</td>
<td>39%</td>
<td>34%</td>
</tr>
</tbody>
</table>

*Heat is thermal energy in motion.*

Heat is the movement of thermal energy from an area of higher temperature to an area of lower temperature. Students often conflate heat with thermal energy, and fail to realize that heat is only thermal energy in motion.

More than half of students in each class failed to understand that energy leaves an egg as it cools down. Only 9% of students in the ETK+D class correctly stated that
energy leaves a cooling egg with most students claiming that "cold" penetrates an egg in order for it to cool down. Over 60% of students in each class indicated that the "coldness" in the air transfers to water in order for it to freeze.

*Heat is transferred from a warmer object to a cooler object.*

Thermal energy only moves from a warmer location to a cooler location. Nothing moves in the opposite direction. Cold, or the lack of thermal energy, does not move. More than 75% of students indicated the alternative conception that cold can transfer from one solid to another. The students lacked an understanding that when two solid objects touch, heat is transferred from the warmer to the cooler object.

More than half of students in each class indicated the alternative conception that cold or temperature can transfer from a cool liquid to a warm solid. Once again, students lacked the understanding that even with liquids, heat transfers from the warmer solid to the cooler liquid, not the other way around.

The majority of students indicated an alternative conception that metal traps or holds "cold" and prevents it from transferring.

*Insulation slows down the rate of heat transfer.*

Many things can slow down the rate of heat transfer. We wear thick clothing in the winter to slow down the rate of heat transfer leaving our bodies. We insulate our attics to slow down the rate of heat transfer in both the summer and the winter. Many students who ascribe to the conception that cold travels, fail to understand the function of
insulation.

Nearly 90% of all students indicated that sweaters keep out the cold, generate heat, and reduce heat loss, representing the alternative conceptions that cold can transfer from a gas to a solid and that that inert fabric can create warmth. Interviews were used to further understand students' conceptions of "cold transfer" and student responses will be described in the section on interviews. More than half of students also indicated that blankets do not warm up dolls because they do not hold heat well. This also confirms the alternative conception that inert objects can create warmth.

*Heat can be transferred across space through radiation.*

Heat can be transferred three ways. Radiation is the transfer of heat through space. Since it is difficult for students to conceptualize that space exists between the atoms and molecules in the air, they may think of radiation as something that only travels in "outer" space.

Most students correctly indicated that light colored clothes reflect radiation. However, one-third of students indicated that heat radiates through a solid, not through empty space.

Most students correctly indicated that black objects absorb radiation, but a good percentage indicated that aluminum foil absorbs radiation better than black objects, illustrating their possible confusion between "absorbing" and "reflecting" radiation, or their lack of understanding about radiation.
Conduction is the transfer of heat through contact.

Heat also transfers through conduction. Conduction occurs when solids touch, or when any matter with a higher temperature touches matter with a lower temperature. Kinetic molecular theory explains conduction. As molecules vibrate due to thermal energy, they cause neighboring molecules to vibrate as well. This chain reaction causes heat to travel. Most students understand after instruction that conduction occurs from a solid to a solid. However, conduction can occur between a solid and a fluid, or between two fluids.

Most students stated that metals are better conductors of heat than wood. One-third of students indicated that metals get hot easily because they melt in fire. This highlighted students' lack of understanding about conduction, radiation and the kinetic molecular theory.

Fluids in motion transfer heat through convection.

Heat also travels through the bulk motion of fluids, whether they be liquids or gases. Differences in density account for the motion of fluids in convection. Warmer fluids are less dense, and rise above cooler, more dense fluids. If these risen fluids cool, they fall. Convection currents can perpetuate if the heating and cooling cycle continues. Approximately half the students indicated a popular alternative conception that "heat" rises, not hot fluids, while an equal number of students indicated a scientific conception that hot air rises and cool air sinks.
Heat and temperature are not the same.

Heat is the transfer of thermal energy while temperature is a measure of the average thermal energy at a particular point in a substance. Students typically have a difficult time differentiating between heat and temperature, and use the two words interchangeably.

More than half the students in each class indicated on the HTE pretest that an aluminum plate is colder than a plastic plate, representing the alternative conception that metals are naturally colder than other materials. This represents a lack of understanding about temperature and thermal energy and heat.

Summary.

In summary, students in all three classes had similar responses on the HTE pretest. They indicated their beliefs that “cold” transfers through fluids, both water and air. They indicated that “cold” travels from one solid to another when they touch. Regarding insulation, they indicated that metals and sweaters both trap “cold” and keep it from transferring. They also tended to indicate that metals are naturally colder than plastics. Most students responded that radiation is reflected off light colored objects and absorbed by dark colored ones, but some indicated that aluminum foil absorbs radiation. While most students understood that metals are good conductors, they did not indicate an understanding of why metals are good at conducting heat. Half the students indicated correctly that hot air rises, but the other half indicated that “heat” rises, an alternative conception based on the belief that heat is a substance. These conceptions, as revealed in
the HTE pretest, are not surprising. Previous research on students’ conceptions of heat transfer and thermal energy revealed similar ideas.

*Entrance Interviews*

Volunteers were elicited from each class for entrance interviews, and 38% of students from the ETK class (6 females and 2 males), 37% of students from the Control class (4 females and 6 males), and 48% of students from the ETK+D class (7 females and 4 males) volunteered to be interviewed about their knowledge and conceptions of heat transfer after completing the HTE pretest but prior to the interventions. One purpose of the entrance interviews was to clarify students’ conceptions about thermal energy and heat transfer after completing the HTE pretest. Another purpose was to determine students’ baseline knowledge about and inclination toward engineering. See Appendix I for the entrance interview protocol.

A one-way ANOVA demonstrated that these three entrance interview groups were statistically equivalent in terms of their knowledge of heat transfer prior to the intervention. The HTE mean for the ETK class interview group ($n = 8$) was $4.38$ ($SD = 2.39$) out of 12 points, the HTE mean for the Control class interview group ($n = 10$) was $4.90$ ($SD = 2.13$) out of 12 points, and the HTE mean for the ETK+D class interview group ($n = 11$) was $4.09$ ($SD = 2.30$) out of 12 points. These three interview groups were each normally distributed (Shapiro-Wilk significance ranged from .244 to .904) with homogeneous variances (Levene’s statistic = .044, $p = .957$). Inferential statistics revealed $F(2, 26) = .339$ and $p = .715$ with an effect size, $r = .11$, demonstrating that the groups were statistically equivalent in terms of their scores on the heat transfer pretest.
Additionally, in order to determine if each interview group represented its class as a whole, independent t-tests were performed. For the ETK class, the interview group earned a mean HTE score of 4.38 (SD = 2.39) while the entire class earned a mean score of 4.33 (SD = 1.83) out of 12 points. This is statistically equivalent at \( t(27) = .05, p = .960 \) with an effect size \( r = .01 \). For the Control class, the subset of interviewed students earned a mean HTE score of 4.90 (SD = 2.13) out of 12 points while the entire class earned a mean score of 4.63 (SD = 1.64). This is statistically equivalent at \( t(35) = .41, p = .684 \) with an effect size \( r = .07 \). For the ETK+D class, the interview subset earned a mean HTE score of 4.09 (SD = 2.30) out of 12 points while the entire class also earned a mean score of 4.09 (SD = 1.81). This is statistically equivalent at \( t(35) = .115, p = .996 \) with an effect size \( r < .001 \). Therefore, these three interview groups can be assumed to represent their respective classes as a whole in terms of how many scientifically correct and alternative conceptions they had about thermal energy and heat transfer.

Interviews were open ended and lasted approximately 20 minutes each. They were transcribed for analysis. Analysis took place in several phases (Bogdan & Biklen, 1992). First, the transcripts were open coded in the search for any and all conceptions about heat transfer and thermal energy. Afterwards, codes, or conceptions, were sorted into the broad categories in which they naturally seemed to fall. These broad categories that emerged were:

1. Conceptions about thermal energy and heat transfer
2. Conceptions about cold
3. Conceptions about insulators
4. Conceptions about metals

5. Conceptions about radiation

6. Conceptions about how objects feel

Prior to the intervention there was no definite pattern to the frequency of scientific and alternative conceptions students held about concepts in these broad categories. Each conception in a broad category was labeled either a scientific conception or an alternative conception. The labeling of items was verified by a professor of mechanical engineering at the University of Virginia whose area of expertise is heat transfer. Frequencies were tabulated for how often each conception was stated by students so that common conceptions could be differentiated from rare ones. Similar conceptions were grouped, and condensed, and from these the most common conceptions were identified. Table 3 depicts how conceptions were expressed by students interviewed from all three classes. A student may have had multiple- or no alternative conceptions- in any category. Therefore the raw numerical values represent the overall number of statements made by interviewed students in any category, and the average number of statements per student are depicted as well.

On average, there were twice as many alternative conceptions expressed by students in all classes as there were scientific conceptions.
Table 3

**Scientific and alternative conceptions before intervention**

<table>
<thead>
<tr>
<th>Category</th>
<th>Scientific Conceptions</th>
<th>Alternative Conceptions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ETK (n = 8)</td>
<td>Control (n = 10)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ETK+D (n = 11)</td>
</tr>
<tr>
<td>Heat/Energy</td>
<td>16</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>Cold</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>27</td>
</tr>
<tr>
<td>Insulation</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>Metals</td>
<td>12</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>27</td>
</tr>
<tr>
<td>Radiation</td>
<td>1</td>
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</tr>
<tr>
<td></td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td>Way objects feel</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>45</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>77</td>
<td>114</td>
</tr>
<tr>
<td></td>
<td>112</td>
<td>130</td>
</tr>
<tr>
<td>Avg. per student</td>
<td>5.6</td>
<td>6.1</td>
</tr>
<tr>
<td></td>
<td>7.0</td>
<td>11.4</td>
</tr>
<tr>
<td></td>
<td>14.0</td>
<td>11.8</td>
</tr>
</tbody>
</table>

Within these six broad categories, the most common **scientific** conceptions stated about heat transfer and thermal energy during entrance interviews by the students in this study were:

1. Bodies generate heat
2. Metal conducts heat or energy
3. Metal gets hot or cold easily
4. Metal reflects heat or light
5. Sweaters do not generate heat
6. Sweaters reduce heat loss
During student interviews, the researcher noted each time a student made one of these commonly stated scientific conceptions. Table 4 lists these most common scientific conceptions and indicates the number and percentage of students in each interview group who articulate the conception during entrance interviews prior to the interventions. Note that sample sizes differed for each class, so percentiles represent the percent of interviewed students who held a particular conception.

<table>
<thead>
<tr>
<th>Conception</th>
<th>ETK  (n = 8)</th>
<th>Control (n = 10)</th>
<th>ETK+D  (n = 11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bodies generate heat</td>
<td>5  (63%)</td>
<td>4  (40%)</td>
<td>6   (55%)</td>
</tr>
<tr>
<td>Metals conduct heat or energy</td>
<td>1  (13%)</td>
<td>6  (60%)</td>
<td>3   (27%)</td>
</tr>
<tr>
<td>Metals get hot or cold easily</td>
<td>4  (51%)</td>
<td>7  (70%)</td>
<td>7   (64%)</td>
</tr>
<tr>
<td>Metals reflect heat or light</td>
<td>2  (25%)</td>
<td>1  (10%)</td>
<td>3   (27%)</td>
</tr>
<tr>
<td>Sweaters do not generate heat</td>
<td>3  (38%)</td>
<td>5  (50%)</td>
<td>7   (64%)</td>
</tr>
<tr>
<td>Sweaters reduce heat loss</td>
<td>4  (51%)</td>
<td>4  (40%)</td>
<td>5   (45%)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>19</strong></td>
<td><strong>27</strong></td>
<td><strong>31</strong></td>
</tr>
</tbody>
</table>

Similarly, within the six broad categories, the most common alternative conceptions stated about heat transfer and thermal energy during entrance interviews by the students in this study were noted and listed below:

1. Cold transfers in from cold to warm
2. Insulators generate heat
3. Insulators are warm, metal is cold
4. Insulators keep cold from transferring
5. Metal traps 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

Table 5 lists these most common alternative conceptions and indicates the number and percentage of students in each interview group who articulate the conception during entrance interviews prior to the interventions. Note that sample sizes differed for each class, so percentiles represent the percent of interviewed students who held a particular conception.

<table>
<thead>
<tr>
<th>Conception</th>
<th>ETK (n = 8)</th>
<th>Control (n = 10)</th>
<th>ETK+D (n = 11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold transfers from cold to warm</td>
<td>5 (63%)</td>
<td>7 (70%)</td>
<td>7 (64%)</td>
</tr>
<tr>
<td>Insulators generate heat</td>
<td>3 (38%)</td>
<td>3 (30%)</td>
<td>2 (18%)</td>
</tr>
<tr>
<td>Insulators are warm, metals are cold</td>
<td>6 (75%)</td>
<td>7 (70%)</td>
<td>3 (27%)</td>
</tr>
<tr>
<td>Insulators keep cold from transferring</td>
<td>4 (50%)</td>
<td>6 (60%)</td>
<td>6 (55%)</td>
</tr>
<tr>
<td>Metals trap or absorb cold</td>
<td>7 (88%)</td>
<td>6 (60%)</td>
<td>6 (55%)</td>
</tr>
<tr>
<td>Heat is always warm or hot</td>
<td>6 (75%)</td>
<td>6 (60%)</td>
<td>6 (55%)</td>
</tr>
<tr>
<td>Heat and temperature are equivalent</td>
<td>3 (38%)</td>
<td>2 (20%)</td>
<td>6 (55%)</td>
</tr>
<tr>
<td>Heat always rises</td>
<td>4 (51%)</td>
<td>1 (10%)</td>
<td>2 (18%)</td>
</tr>
<tr>
<td>Dark objects attract heat</td>
<td>3 (38%)</td>
<td>2 (20%)</td>
<td>1 (9%)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>41</td>
<td>40</td>
<td>39</td>
</tr>
</tbody>
</table>

These tables demonstrate that students had similar ideas across class prior to the interventions. While some variation existed within a certain category, on a whole there
were equivalent numbers of alternative and scientific conceptions expressed by students in each class during entrance interviews, with the number of alternative conceptions expressed outweighing the number of scientific ones.

In the following sections, students' conceptions within each of the six broad categories will be explained, and examples provided.

Conceptions about thermal energy and heat transfer.

The most common scientific conception about heat and energy was that bodies generate heat. Out of 29 students interviewed, 15 made this statement. However, only 5 of the 29 knew that heat is generated by friction or molecular motion, and only 1 stated that liquid water contains thermal energy, so these conceptions were not included in the list of the most common. Some students may not have articulated all their scientific conceptions about heat and energy, but overall over half the students in each interview group made at least one scientifically correct statement about heat and thermal energy. The following quote is typical of the scientifically correct statements made about body heat by students in their entrance interviews.

When you are getting out of a pool, and you’re cold, you wrap a towel around you to insulate yourself so your heat will heat you up. (Chuck, Control class, entrance interview)

Alternative conceptions about heat and energy were stated more frequently than scientific conceptions in all three classes. There were roughly equal numbers of alternative conceptions about heat and energy across the three classes prior to the intervention. The most prevalent alternative conceptions were that heat is warm, that
metals trap cold, and that cold transfers. Other less popular alternative conceptions were that heat rises and sweaters generate heat.

The following quote is typical of the types of alternative conceptions stated about heat and energy by students during their entrance interviews.

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)

Conceptions about cold.

Students could correctly state that metals react to cold temperatures, but could not identify why. Only one student in the entrance interviews correctly defined cold as the lack of thermal energy. “When something is cold it doesn’t have that much energy, it doesn’t have that much heat (Ed, ETK+D class, entrance interview).

Most students identified “cold” as a substance that transfers or can be trapped, much like heat, which they perceived to be always warm. Students especially perceived metal to be a substance that attracts and traps cold, and justified that metal is colder than other materials like plastic and wood because of this ability to trap and hold the coldness. “Metal can also get cold easily. I’ve had experience with that. Sometimes when I touch metal railings they feel really cold.” (Bill, ETK+D class, entrance interview)

The following statements are typical of the alternative conceptions students held about cold prior to the interventions.

When you lift up the soda off the counter, the counter is cold. The cold goes to the counter. (Kate, ETK class, entrance interview)

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)
Conceptions about insulators.

The most common scientific conception about insulators was that they trap heat and do not generate it. Students could correctly identify plastic, wood, wool, and air as insulators.

The following quotes are typical of the scientifically correct statements made about insulators by students in their entrance interviews.

The sweater itself does not generate heat. We generate heat, our own heat, and the sweater keeps it in. (Daniel, ETK class, entrance interview)

You reduce the heat loss by keeping something around you so the heat doesn’t escape. (Jim, Control class, entrance interview)

The most common alternative conception about insulators was that sweaters keep out cold, a repetition of the idea that cold transfers like a substance and can be stopped from transferring. Students may have been thinking about cold air transferring through sweaters, but they consistently referred to "coldness" as if it were a substance. They explained that coldness transfers from water to a hot egg, and from a cold soda to a counter. Likewise, they explained that coldness transfers from the outside air to the body wrapped in a sweater.

While students could identify plastic and wool and wood as insulators, they were not sure why those materials had insulating properties. Students articulated alternative conceptions about insulators almost twice as often as scientific conceptions.

The following dialog is typical of the alternative conceptions expressed about
insulators by students in their entrance interviews.

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.

Conceptions about metals.

Students primarily had conceptions about the relationship between metal and heat/temperature through their direct observations. They had experience with how hot metals can get in the sunlight or oven, and also how cold metals can feel when touched outside in the winter or in the freezer.

The following quotes are typical of the scientifically correct statements made about metals by students during their entrance interviews. While these statements may be considered technically correct, they reveal an underlying misunderstanding about why metals actually do feel colder or hotter than insulating materials.

Metal can get hot and it also can get very cold. Like the door knob, if it’s very cold. It’s like putting your tongue on a metal pole. It is very cold. (Daniel, ETK class, entrance interview)

The handle to the outside of my door in the winter time can be really cold... and my seatbelt, if it’s really hot and we leave the windows open, it burns and I can’t even touch it. So I would think that it attracts more, but I could still pick up a log or something. (Paul, Control class, entrance interview)

The most prevalent alternative conceptions about metals were that they trap cold, absorb cold, and keep in “coldness.”

The following quotes are typical of the alternative conceptions stated about metals by students prior to the intervention.
In the winter, metal is colder. Maybe it absorbs more coldness. (Marlene, ETK class, entrance interview).

I know everybody puts aluminum foil on top of a pie or something and then puts it in the fridge. So if you want to keep it cold you put the aluminum foil over it and it like traps the coldness inside of it so it doesn’t like let it out. (Dara, ETK+D class, entrance interview)

While not many students explicitly stated that metals are insulators, that conception was implied by their many statements about how they perceived metals to trap and collect “cold waves” or keep cold from transferring.

Conceptions about radiation.

Not many students discussed radiation in their entrance interviews. They brought up some concepts related to radiation, such as the fact that dark colors can get hotter than light ones. Basically, students did not know very much about radiation at all prior to the unit on heat transfer.

The following quotes are examples of the scientific conceptions articulated about radiation by students in their entrance interviews.

I would make it (a baseball cap) white because black usually gets hot... Like, if you have a black car as opposed to a white car, it gets hotter. (Casie, ETK class, entrance interview).

If you used a lighter color it will reflect the heat off. (Robbie, ETK+D class, entrance interview).

Many students stated that dark colors “attract” the sun or heat, not understanding that colors are inert, exerting no forces to attract radiation or sunlight. They may have been confused about terminology, conflating the word, “attract”, with the word, “absorb.” They also did not seem to have made the connections between sunlight and radiation, and
energy and heat. The following quote is typical of the alternative conceptions expressed about radiation by students in their entrance interviews.

It’s going to be a light color (the baseball cap) because I don’t want the sun to attract to it if it’s black. (Robbie, ETK+D class, entrance interview)

Conceptions about how objects feel.

Only 2 students out of 29 interviewed could correctly predict that objects of the same temperature can feel different, as Sakura did in the excerpt below:

Some substances, the temperature is the same but when you touch them it feels different, like one feels cold and one feels hot but the thermometer says it’s the same. (Sakura, ETK+D class, entrance interview)

Primarily, students from each class stated that metal is cold while plastics and wood are warm. When asked whether an aluminum plate and a plastic plate would have the same temperature in a freezer, Sarah replied:

Because the aluminum plate, it’s going to get colder and the plastic one is not going to collect the coldness from the freezer while the aluminum plate is going to. (Sarah, ETK class, entrance interview)

Students had a definite conception that no matter what temperature it was in the surroundings, plastics and metals placed there would have different temperatures. The following quote is typical of statements made about this topic during the entrance interviews.

Metal in a cold area would ... be more cold than the wood because I don’t think wood would really give off or take in as much energy as the metal one would. Metal seems to get colder faster in a cold environment than wood does. (Chuck, Control class, entrance interview)
Summary of Heat Transfer Conceptions Prior to Intervention

Interviewed participants seemed to be familiar with everyday experiences with heat and temperature. They talked about body heat and how sweaters, hats, and towels trap body heat—although some students thought that sweaters actually generated heat. Few students understood that thermal energy that comes from the motion of molecules and the friction between molecules; most students thought of heat as always warm, the opposite of cold, and that temperature is what measures heat.

Students could correctly state that metals feel cold while wood and plastics feel warm, but could not articulate the scientific process causing this feeling. Instead, students conceived that metals absorb cold, imagining cold to be some sort of substance that flows, getting trapped and absorbed like heat. Alternatively, students identified that in hot weather metals feel hot while plastics feel cooler, but they still could not explain the correct scientific reason for this.

Radiation as a type of heat transfer was a concept only understood in terms of how dark objects tend to become hotter than light colored objects when exposed to sunlight. However, students could not explain why, other than to say that dark colors absorb or attract heat, and that light colors reflect or repel it.

While two students stated that objects can have the same temperature while feeling different, most students articulated that if an object felt cold, it was cold. If an object felt warm, it was warm. All of 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.

Conceptions of Heat Transfer during the Intervention

During the intervention period, the ETK class was taught heat and energy through the engineering design ETK, *Save the Penguins*, but without five demonstrations designed to target alternative conceptions about heat transfer. See Appendix A for the complete *Save the Penguins* curriculum. Instead, students participated in the ETK, but with demonstrations that the teacher typically conducted for her classes during her unit on heat transfer and thermal energy. The rationale for using two different sets of demonstrations was to determine whether those designed specifically to target research-based alternative conceptions might have an effect on student learning above and beyond the engineering design treatment.

The “typical” demonstrations used by the teacher were: food coloring in cold and warm water, balloons in the freezer and the room, a beaker of ice cubes placed in a beaker of boiling water, and demonstrations performed by Bill Nye on a 26 minute video about heat (Nye, 1996). These demonstrations will be described in detail later in this chapter. The Control class was taught about heat and energy in the manner that the teacher typically taught it, primarily through book readings, labs, the typical demonstrations, computer simulations, and the Bill Nye movie. The ETK+D class was taught about heat and energy with the entire *Save the Penguins* ETK, complete with the five demonstrations designed to target alternative conceptions. These demonstrations were: the cans, the trays, the spoons, the house, and the Mylar. They will be described in detail later in this chapter. In an effort to track changes over time, students were observed
during the intervention, given microphones to talk into during lab time or group work, and given written journal activities.

**Assertion 2: Students' conceptions of heat transfer changed during instruction depending on which treatment they received.**

Students in the three classes had different experiences and ways of understanding or not understanding concepts related to heat and energy during the interventions. During each of the three different interventions, the researcher took field notes in the classroom, and for back-up, video and audio taped the classroom from the side with a lavaliere microphone on the teacher as well as a microphone on the camcorder. The researcher had three wireless microphones that sent signals to digital voice recorders. Whenever students were involved in group or lab work, three sets of students were given microphones. Preference was given to students who were participating in entrance and exit interviews, however other groups were chosen as well. The audio was transcribed for analysis. The researcher walked around the classroom during activities and transcribed student discourse. While the researcher made a concerted effort not to verbally interact with students during these walk-arounds, brief conversations did occur on occasion with students in all three classes. Students became more comfortable with the researcher in the classroom over time, and initiated these conversations. However, the researcher made every effort not to interfere with the classroom activities and become part of the treatment. Data were also taken from journal activities that all students were required to participate in regardless of the intervention.

To substantiate the assertion that students' conceptions of heat transfer and
thermal energy changed during the treatment depending on which treatment group they were in, examples and excerpts from discussions will follow.

Treatment Groups

ETK Class

The following excerpt is from day 4 of the unit in the ETK class as students and teacher discussed materials available for purchase:

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 conduction? 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 were using knowledge they gained from their materials testing to inform their design decisions. They demonstrated an 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 one group in the ETK class was having while trying to re-design their dwelling for the second test in the hot oven.

Reggie: I was thinking we could do something to make more shade and block radiation.
Daniel: If we have air as an insulator right here, another layer, I say...
Margaret: We found this stuff heated up a lot.
Daniel: I think it reflects, also so it can be on the roof with something under.
Reggie: Maybe instead of having metal at the bottom...
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.
Reggie: Do we have enough money?
Daniel: I think we need 4 more Popsicle sticks to raise it off the ground. Do we have unlimited tape?

(Reggie makes a tube out of a square of green construction paper.)

Reggie: We don't need Popsicle sticks, we can just make this piece of paper for a tube and that will keep it off the ground.
Daniel: We need to make a few of those.

The students were thinking about the materials in terms of which ones were affordable, which ones would provide shade from the radiation, which ones would reflect radiation, and which ones were good insulators. They made creative use of inexpensive materials available to them. They discussed air as a good insulator, using a reflective material on the bottom of the dwelling to reflect radiation from the black floor, using light colors instead of dark ones, and reducing conduction by raising the dwelling off the floor.

Students 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.
Control Class

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.

On day 3 of the unit, students in the Control class were involved in a research activity. They were working in pairs at computers, learning about how different materials prevent heat transfer. The following excerpt is from a conversation between two boys researching fabrics:

Paul: What types of fabrics are better insulators?
Woody: I think that Gore Tex is the best.
Paul: I like wool or dog.
Woody: So Paul, what do you think the best insulator is before we get started?
Paul: Probably wool.
Woody: I think Gore Tex is the best.

Students were on their own for the most part during this activity. The teacher walked around from group to group to make sure students were on task, but did not engage them in challenging conversations. They were not using the terms and definitions they learned from class or homework assignments, nor were they using any socially constructed knowledge about heat transfer and thermal energy.

On day 4 of the unit, students worked in pairs at computers on a simulation about conduction. They were given a handout of questions to answer as they manipulated this simulation and changed the material connecting two beakers of water at different temperatures. It was unclear from the simulation whether the materials connecting the two beakers were supposed to be solid or hollow, but students should have been able to infer that the materials were solid and that water was not passing from one beaker to
another. The following excerpt is from a conversation between the teacher and a student working on the simulation by himself because his partner refused to participate:

Teacher: So what happened?
Mark: It's kind of like a level that evens out if it's equal.
Teacher: How did the temperature equal out?
Mark: You pressed play.
Teacher: In real life, how would heat get from one to the other?
Mark: The aluminum tube.
Teacher: Did water flow through the tube?
Mark: The heat transferred
Teacher: It's probably a solid piece of material. Do you think convection went through it?
Mark: It would be either convection or conduction.

From this excerpt it is clear that the student did not know the difference between convection and conduction, and thought perhaps water was moving from one beaker to another. The students were told to run this simulation with all the different types of materials available and observe and record any differences. The other materials were copper, steel, and glass. Students in the Control class were not developing clear understandings of conduction through this activity. They were strong students, listened in class, and did their homework. The knowledge gains they made in understanding about heat transfer and thermal energy were through reading and listening instead of debate, discussion, and cognitive dissonance.

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ETK+D Class

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. The following is an excerpt from the class discussion following the demonstration with the six cans of soda wrapped in different materials:

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.
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 conception that aluminum foil keeps things cold.

The following is an excerpt from the class discussion during the demonstration with the trays made from silver and plastic:

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.

Since students all concluded that the silver tray was colder than the plastic one, they all predicted that a silver spoon would keep an ice cube frozen longer than a plastic spoon. They were wrong. 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.

The following is an excerpt from the class discussion during the spoons 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

Students could see how heat transfer 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. Dara was observed
during this demonstration remarking, “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.” The spoons demonstration took 15
minutes, and it provoked rich dialog about heat transfer.

When students were shown the thermometers taped underneath the silver and
plastic trays, and realized that the trays were both room temperature, they were shocked
and amazed that their senses could fool them. Dara said out loud, “That's just freaky. It's
scary!” This demonstration with the trays 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 demonstration also gave students the opportunity to discuss heat
transfer and imagine convection currents in something other than the standard pot of
boiling water. After the house was heated up, the teacher flipped it upside down. She
asked her class:

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.
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 demonstration with the Mylar also proved to be very useful to students as they designed dwellings for their penguin-shaped ice cubes. Most student teams subsequently covered their dwellings in Mylar.

As students in the three different classes worked toward the same learning objectives, it became clear that they were learning in quite different ways, and their scientific conceptions changed in different ways as well. The following section describes in greater detail how conceptions changed in different ways in each class.

*Conceptions about Heat and Energy*

Students stated the correct concept that “hot air rises” during the intervention, with students in the ETK+D class stating it more than students in the other classes. Overall, students in the ETK+D class made more correct statements about heat and energy during the intervention than students in the other classes. The only students to state that warm air rises and cool air sinks were students in the ETK+D class. The only students to state that conductors, when held, can take heat away from the body were in the ETK+D class. This concept can probably be directly tied to a demonstration where students held silver and plastic spoons containing ice cubes.

Recall that the ETK+D class received the entire ETK along with the five demonstrations designed to target alternate conceptions.
Lizanne, a student in the ETK+D class answered the journal question, “Why is it usually hotter in the attic of a house” with the answer, “Warm air rises so the warm air floats up to the top of the house while the cold air sinks to the bottom” whereas Jim, a student in the Control class answered the same journal question with, “It is warmer in the attic because heat rises from the basement up.” These answers were typical of students in these two classes. During a PowerPoint lecture, Zack, a student in the ETK+D class stated out loud, “Hot air goes up and is forced into the place where the cold air was and the cold air sinks. Cool air doesn't go up; the hot air goes up there.” Perhaps the demonstration with the house allowed Zack to conceptualize this idea.

A group of students in the ETK class were discussing their design and the following conversation was overheard:

Emily: The roof is like an attic.

Walt: Why do we need an attic?

Dave: Because hot air rises.

Dave understood the concept that hot air rises, but was not able to explain it in the way that Zach in the ETK+D class did.

The alternative conceptions that “heat rises” was predominately stated by students in the Control class during the intervention. Nearly half the students in this class made this statement at some time during the intervention. Fewer students made this statement in the engineering design classes. While students in the Control class made the most incorrect statements about heat and energy during the intervention, students in the ETK+D class made the fewest number of incorrect statements.
Conceptions about Cold

Students in The ETK+D class made fewer incorrect statements about “cold”. Whereas 3 students in the ETK class stated that cold transfers and 2 students stated that coldness exists, no students in the Control class made those statements and only 1 in the ETK+D class said anything along those lines during the unit.

The most common incorrect statements made about cold during the unit were in the framework of “cold” as a substance. When asked in a journal exercise whether she would prefer to hold onto a wooden or a metal bar in the wintertime without gloves, Kate in the ETK class replied that she would “hold onto the wooden bar because it conducts less cold…” Callie, a student in the Control class stated in a journal entry that “heat rises and cold sinks.”

Conceptions about Insulators

There were very few incorrect statements made about insulators during the intervention.

One student in the Control class stated that wood does not react to temperature, and one student in the ETK+D class stated that wood attracts heat. Three students stated that wood is not a conductor. While it is considered an insulator and a poor conductor, wood indeed conducts heat, just not as well as some other materials.

Conceptions about Metals

Students in the ETK+D class had a substantially lower number of alternative
conceptions about metal during the intervention.

When asked in a journal exercise whether he would prefer to hold onto a wooden or a metal bar in the wintertime without gloves, Walt, a student in the ETK class replied that he would “grab the wood bar because it will not get as cool as the metal bar.” Mark, a student in the Control class replied that he would hold onto the wooden bar because “the wooden bar... doesn't collect heat or cold like metal, so it wouldn't be cold like metal.” However, Mike in the ETK+D class correctly stated that he would hold onto the wooden bar because “it would take less heat from my hand.” This explanation may hearken back to the demonstration with the two different spoons.

The ETK+D class was having a discussion on the second day of the unit about metals and heat. An excerpt of that discussion follows:

Teacher: Start thinking about what a conductor is. Come up with a definition.

Robbie: Something that easily transmits heat.

Ed: No, it's something that attracts heat.

Sakura: So conductor is something that transmits heat easily, like a pot. Like metal.

Zack: Metals like copper and steel.

A few days later 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. Actually one group in the ETK+D class initially wrapped their ice cube in a tube of aluminum foil (Figure 11). However after testing, they redesigned the device using felt instead with foil plugs at each end (Figure 12).

Figure 11. First dwelling design from Group E in the ETK+D class.
Few students had a true conception of radiation during the intervention. There were very few scientific conceptions articulated and roughly equivalent numbers of alternative conceptions. The most interesting alternative conception was that attics are hot because they are closer to the sun. Fewer students in the ETK+D class made this statement, perhaps because they had a better conception of attics being warm because of the hot air rising due to the demonstration with the cardboard house.

Kate, in the ETK class, like other students who articulated this concept, stated that “The attic is closer to the top of the house where the sun beats down onto the house. It’s the first place the Sun is.” Only one student in the ETK+D class, Bonnie, articulated this concept, stating that “the attic is closer to the Sun’s radiation.”
Conceptions about How Objects Feel

Only one student, Ed, in the ETK+D class articulated during the intervention that objects with the same temperature can feel differently. The teacher was introducing the spoons demonstration and students were making predictions. While Robbie predicted that the silver spoon would keep the ice cube from melting because the metal itself is colder, Ed was able to point out that just because silver feels colder, it is not necessarily a different temperature.

Teacher: For demonstration three, each group is going to get two spoons; an actual silver spoon and a plastic spoon. Again, make your prediction. Which will keep an ice cube cold longer?
Robbie: Silver, because the silver is colder.
Ed: It isn't colder, it just feels colder.

Students in all three classes made statements that not only do metals feel colder, they actually are colder than wood and plastic, but more students in the ETK class held this conception.

When all students were asked in a journal activity whether they would prefer to hold onto a metal bar or a wooden bar in the wintertime without gloves, students predictably replied in writing:

"I would grab the wood bar because it will not get as cool as the metal bar" (Walt, ETK class).

"The brown wooden bar because it does not conduct heat so it would be warmer than the metal bar" (Adam, Control class).

"I would hold onto the wooden bar because it wouldn't be as cold as the metal bar. The wooden bar wouldn't be as cold because wood is a better insulator and would keep the warmth in unlike the metal" (Amy, ETK+D class).
Summary of Heat Transfer Conceptions during the Intervention

Prior to the intervention, students in each class had similar conceptions about heat and energy. During the intervention, all classes acquired knowledge about heat transfer and thermal energy through different activities, and to different degrees.

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. This is most likely due to the house demonstration and the discussion about hot and cool air switching places when the house was flipped. 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.

Many students retained the alternative conceptions that attics are hot because they are closer to the Sun. Working with heat lamps probably reinforced this conception because objects closer to the heat lamp indeed were of higher temperature. Students in all
three classes also occasionally made statements that heat falls out of things, and that heat particles exist. During the intervention more students made the scientific statement that cold air sinks. Whereas the number of students stating alternative conceptions about cold prior to the intervention was roughly equivalent, the number of stating alternative conceptions about cold during the intervention was not equivalent across treatment groups. While students in all three classes had direct experiences with ice cubes melting, students in the ETK+D class exhibited fewer alternative conceptions about cold.

Much was said about insulation during the intervention. 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.

The number of scientific conceptions about metals changed during the intervention. Prior to the intervention, students in the Control class and the ETK+D class made the same number of scientifically correct statements about metals and their relationship to heat. During the intervention, a much larger number of students in the
ETK+D class made scientifically correct statements about metals and their relationship to heat. Whereas only 2 students in the entrance interviews stated that metals are good conductors, 20 students made this statement during the intervention, and nearly half of those were from the ETK+D class. This could be due to their experiences with aluminum foil during the dwelling construction, or it could have been the influence of the spoons demonstration. The number of alternative conceptions about metals dropped during the intervention in all three classes, but that drop was greatest in the ETK+D class. Only 4 students in the ETK+D class made an incorrect statement about metals during the intervention, whereas 9 students in the ETK class and 12 students in the Control class made incorrect statements. Prior to the intervention, there were equivalent numbers of students making incorrect statements about metal and its relationship to heat transfer and thermal energy.

The topic of radiation was discussed more frequently in the two engineering design classes during the intervention. This is probably due to the fact that students in the engineering design classes were using a hot box with a black bottom to test their designs, and they were testing materials with heat lamps, attempting to block or reflect radiation from the lamps.

Conceptions of Heat Transfer and Thermal Energy after the Intervention

Posttests and exit interviews were used after the intervention to determine how students' conceptions of heat transfer changed depending upon which intervention they received. In this section both qualitative and quantitative data from exit interviews and the HTE posttests will be presented. Results indicated that while all three classes on
average made statistically significant gains from pre- to posttest, students in the ETK+D made greater gains than the other two classes and demonstrated deeper conceptual understanding about heat transfer and thermal energy. In this section, results from the HTE posttest and exit interviews will be presented. These results, along with results from exit interviews with students in each class, support the third 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.

Assertion 3: 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.

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 each of the three classes in terms of students’ answers on the Heat Transfer Evaluation. In all cases, \( p < .001 \). The ETK class, \( n = 21 \), obtained a HTE 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 HTE 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 HTE posttest mean score of 8.22 (SD=1.94) with a change of 4.22 out of 12 points.

Inferential statistics were used to determine if there were differences between classes. 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 $r = .29$. Running pairwise comparisons, there was a significant interaction between the pre and posttests scores in the ETK class and pre and posttest scores in the higher achieving ETK+D class across time with $p = .003$. There was also a significant interaction between pre and posttest scores in the Control class and the higher achieving ETK+D class across time with $p = .036$ while the difference across time between the ETK class scores and the Control class scores was not significant with $p = .842$. Figure 13 illustrates the interaction between student achievement on the HTE and time.

Figure 13. The interaction between class scores on the HTE pre- and posttest
Table 6 illustrates the percentage of students from each class who answered each question on the HTE pre- and posttest with the correct answer. See Appendix F for questions on the HTE instrument. The percentage of correct scores increased in all classes on all but four items. Fewer students in the ETK class answered questions 4 and 11 correctly, fewer students in the Control class answered questions 4 and 12 correctly and the same number answered question 6 correctly, and the same number of students in the ETK+D class answered question 4 correctly.

Table 6

<table>
<thead>
<tr>
<th>Question</th>
<th>ETK Class (n = 21)</th>
<th>Control Class (n = 27)</th>
<th>ETK+D Class (n = 23)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pre</td>
<td>post</td>
<td>pre</td>
</tr>
<tr>
<td>1</td>
<td>24%</td>
<td>52%</td>
<td>11%</td>
</tr>
<tr>
<td>2</td>
<td>38%</td>
<td>57%</td>
<td>22%</td>
</tr>
<tr>
<td>3</td>
<td>10%</td>
<td>38%</td>
<td>7%</td>
</tr>
<tr>
<td>4</td>
<td>33%</td>
<td>24%</td>
<td>48%</td>
</tr>
<tr>
<td>5</td>
<td>14%</td>
<td>62%</td>
<td>15%</td>
</tr>
<tr>
<td>6</td>
<td>71%</td>
<td>95%</td>
<td>89%</td>
</tr>
<tr>
<td>7</td>
<td>90%</td>
<td>86%</td>
<td>93%</td>
</tr>
<tr>
<td>8</td>
<td>48%</td>
<td>52%</td>
<td>59%</td>
</tr>
<tr>
<td>9</td>
<td>14%</td>
<td>33%</td>
<td>11%</td>
</tr>
<tr>
<td>10</td>
<td>29%</td>
<td>52%</td>
<td>30%</td>
</tr>
<tr>
<td>11</td>
<td>5%</td>
<td>0%</td>
<td>4%</td>
</tr>
<tr>
<td>12</td>
<td>57%</td>
<td>90%</td>
<td>74%</td>
</tr>
<tr>
<td>Overall</td>
<td>36%</td>
<td>54%</td>
<td>39%</td>
</tr>
</tbody>
</table>

Difficulty with question 4, regarding why blankets do not warm up dolls, was consistent across class. The following sections describe students' conceptions related to
the targeted teaching objectives derived from national standards.

*Heat is thermal energy in motion*

A majority of students in each class correctly stated that energy leaves a hot egg while it is cooling, as opposed to cold from the surrounding water being transferred into the egg. The vast majority of students in the ETK+D class stated this correctly, while approximately half the students in the other classes did so. However, some students held onto the notion that cold would transfer into a cooling egg.

*Heat is transferred from a warmer object to a cooler object*

The majority of students in each class stated that heat would be transferred from a warmer countertop to a colder soda placed on top, with 78% of students in the ETK+D class stating this correctly. The following quotation is typical of the correct explanations students gave in the exit interviews.

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)

The majority of students in all three classes answered correctly that air in a freezer would absorb heat from water when the water freezes instead of stating that the water absorbs "coldness" from the freezer. Prior to the intervention, over 60% of students stated that water absorbs the coldness from the air. On the posttest however, 62% of students in the ETK class, 70% of students in the Control class, and 70% of students in The ETK+D class stated that heat transfer occurs from the warmer water to the colder freezer air.

Some students, however, like Jenny, a student in the ETK class, retained their deeply held
conceptions of cold transfer despite instruction to the contrary as can be seen in the following excerpt from her exit interview:

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).

However, Sakura, a student in the ETK+D class, who had a total lack of understanding prior to the intervention, described a much different, more scientific conception about ice freezing in her exit interview.

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)

**Insulation slows down the rate of heat transfer**

A majority of students in each class held onto the conception that sweaters not only reduce heat loss, but generate heat and “keep out the cold” as well. There may have been some ambiguity and inherent limitations with this question as students may have been thinking of how clothing may block cold air from blowing inside towards the skin. It was common for students in all three classes to incorrectly state that sweaters keep out the cold, but correctly answer the first two questions on the HTE posttest indicating an understanding of the directionality of heat transfer. The exit interviews were able to tease out what students were actually thinking, and many of them were thinking about a sweater or other cold-weather clothing blocking the transfer of cold air. Even some students who correctly answered that sweaters reduce heat loss, admitted during exit
interviews that they believe sweaters to keep cold out. Perhaps this idea came from the Bill Nye video shown to the ETK class and the Control class. Nye was talking about coats, hats, and gloves, and stated, “It keeps out the cold. It keeps you warm. It keeps in the heat.” Cold is not a substance that transfers, although cold air is. Students seemed to be conflating cold air with “cold.”

Daniel in the ETK class explained that sweaters reduce heat loss but do not generate heat or keep out the cold. He understood that cold was a term signifying lack of heat and that only heat transfers.

Researcher: Why did you say (sweaters) reduce heat loss?
Daniel: Because again, it doesn’t generate heat, we generate heat- the sweater doesn’t. Cold doesn’t move, and if the heat can’t be transferred to the cold air, we don’t lose as much heat keeping us warm.

Researcher: How did you learn what you just said, “cold doesn’t move”?
Daniel: Because cold technically really doesn’t exist because there’s only heat and then there’s absolute zero which is the lack of heat.

Students still had trouble after the intervention explaining why a blanket will not warm up a doll. Most students in all classes stated incorrectly on the pretests that blankets do not warm up toy dolls because “dolls are made of materials which do not hold heat well.” After the intervention, more students answered this question correctly, with 43% of students in the ETK+D class choosing the correct answer, “None of the above” possibly demonstrating an understanding that dolls do not generate heat. This was a tricky question to answer. Students typically got this question correct if they had a high score on the HTE posttest (9 or above) and understood the concepts well, or if they got a low score on the HTE posttest (5 or below) and were probably guessing. The interview responses
helped clarify students’ ideas about that question.

Since dolls don't usually make their own heat, then I didn't really see how any of them could really help them keep warmer because there's no heat going from them in the first place. (Chuck, exit interview, Control class)

All students in the ETK+D class stated that wool would be the best material of the four choices to keep a can of soda cold. Only 33% of students in the ETK class and 22% of students in the Control class came to this conclusion. The cans demonstration, which was shown only to students in the ETK+D class, most likely accounted for this difference. Students in the ETK+D class were presented with a discrepant event which provoked cognitive dissonance and likely encouraged some changes in conceptions about insulators and conductors.

Jenny, a student in the ETK class, chose aluminum foil on both the pretest and the posttest. In her exit interview, she explained why. This quotation demonstrates that the design challenge alone was not enough to help this student with her conceptions about insulators and conductors.

I haven’t tried the wax paper thing yet so I stuck with the aluminum foil. And when we did the penguin thing and we had the little piece of aluminum foil, it didn’t gather as much heat as the space blanket stuff, so I just kind of stuck with that. (Jenny, exit interview, ETK class)

Paul, a student in the Control class, answered in a way typical of his classmates, explaining his choice of aluminum foil based on intuition.

I've just noticed that when I put aluminum foil around hot things, like to keep the air trapped inside of it, so I would think that if you put aluminum foil around the cold things it would keep the cold air trapped inside. I’ve never actually wrapped up Coca-Cola in any of those things (Paul, exit interview, Control class).

However, Julie- who had been exposed to the cans demonstration like the rest of her
classmates was able to make sense of the question and answer with a scientifically correct explanation.

Because I learned that wool and cotton were good insulators and it would keep the thermal energy from penetrating into the soda and make it warm (Julie, exit interview, ETK+D class).

*Heat can be transferred across space through radiation*

The majority of students in all three classes correctly stated that light colored clothes are cooler because they reflect radiation. While all students in the ETK+D class answered this question correctly, 61% of students in the control class did so. Some students in the ETK class retained the idea that light colored clothes are cooler because they let more air in,

Once again, most students stated correctly that a black sweater placed in the sunlight would absorb more radiation than a white sweater, a snowball, or aluminum foil. Seventy percent of students in the Control class and 83% of students in the ETK+D class answered this correctly- a large change from the pretest responses.

*Conduction is the transfer of heat through contact*

Most students correctly stated that metal conducts heat better than wood. However, still some students retained the idea that heat is “attracted to” metals, not understanding the molecular theory that underpins conduction.

*Fluids in motion transfer heat through convection*

Some students retained the concept that “heat rises” after the intervention, but fewer students in the ETK+D class retained this concept. In the ETK class, 43% of
students still claimed that "heat rises." In the Control class, 15% said that "heat rises." In the ETK+D class, only 13% said that "heat rises." Perhaps the cardboard house demonstration shown to students in the ETK+D class helped students modify this alternative conception that heat is a substance that always rises. Dara, a student in the ETK+D class explained her thoughts on this subject:

> Everybody says that heat rises but it's actually not true, which I told my mom last night, it's hot air that rises, so of course the attic is going to be very hot and then since the hot air rises, the cool air will kind of stay in the first level. (Dara, exit interview, ETK+D class)

*Heat and temperature are not the same*

When asked about the temperatures of a plastic plate and an aluminum plate, none of the students in the ETK class correctly answered that the two plates would have the same temperature if they were in a freezer. Most said that the plastic plate would be warmer than the aluminum plate. Thirty seven percent of students in the Control class students answered the question correctly, stating that the two plates would have the same temperature while 34% of students in the ETK+D class answered the question correctly. The spoons and trays demonstrations may have affected student performance on this question.

*Summary*

Students were more likely after the interventions to understand that heat is the transfer of thermal energy from a warmer place to a cooler place. Students in the ETK+D class were more likely than other students to articulate this. Students remained somewhat confused in each class about the role of insulators, with some still thinking that insulators
prevent cold from transferring or actually created thermal energy. Students in the ETK+D class were more likely than students in other classes to choose wool as a good insulator to keep a can of soda cold, and were able to articulate that the wool prevented heat from transferring to the cold soda. Students were mostly clear on the fact that light colors reflect radiation while darker ones absorb it. Students in the ETK+D class were more likely to articulate this concept correctly. While nearly half of the ETK class students stated that “heat rises”, only 15% of Control class students and 13% of ETK+D class students made this statement. Students in all three classes continued to confuse heat and temperature after the intervention.

Exit Interviews

The same 8 students in the ETK class who participated in entrance interviews—plus 2 additional students—participated in the exit interviews for a total of 10 students. The additional students volunteered after the researcher made an open request for more participants. The same 10 students in the Control class who participated in the entrance interviews also participated in the exit interviews. Two students in the ETK+D class who had participated in entrance interviews decided not to participate in an exit interview, and one student not interviewed prior to the intervention decided to participate in an exit interview. Since these groups of 10 students each were slightly different, the groups of students were compared to the each other in terms of their Heat Transfer Evaluation pretests to determine whether they were equivalent groups in terms of their beginning knowledge about heat. A one-way ANOVA demonstrated that these three exit interview groups were statistically similar in terms of their knowledge of heat transfer prior to the
intervention. The pretest mean on the heat transfer evaluation for the ETK class exit interview students ($n = 10$) was 4.30 ($SD=2.16$), the pretest mean for the Control class exit interview students ($n = 10$) was 4.90 ($SD=2.13$), and the pretest mean for the ETK+D class exit interview students ($n = 10$) was 4.70 ($SD=2.16$). In this case, $F (2,27) = .201$ and $p = .819$ with an effect size $r = .08$, demonstrating that the groups were statistically similar in terms of their scores on the heat transfer pretest.

It was also important to determine whether each interview group represented the class from which they originated. So, $t$-tests were performed to determine this. They revealed that each subset of interview students was equivalent to the whole class on the pretest. For the ETK class, the subset of interview students earned a mean score of 4.30 ($SD=2.16$) on the HTE pretest while the entire class earned a mean score of 4.33 ($SD=1.83$). This is statistically equivalent at $t (29) = .045, p = .965$ with an effect size $r = .01$. For the Control class, the subset of interview students earned a mean score of 4.90 ($SD=2.13$) on the HTE pretest while the entire class earned a mean score of 4.63 ($SD=1.64$). This is statistically equivalent at $t (35) = .41, p = .684$ with an effect size $r = .07$. For the ETK+D class, the subset of interview students earned a mean score of 4.70 ($SD=2.16$) on the HTE pretest while the entire class earned a mean score of 4.09 ($SD=1.81$). This is statistically equivalent at $t (31) = .844, p = .405$ with an effect size $r = .15$. Therefore, each of the three interview groups could be assumed to represent their respective classes as a whole.

The most common scientific conceptions stated about heat transfer and thermal energy during exit interviews by the students in this study were:
1. Even cold things have heat.

2. Heat comes from friction and the motion of molecules.

3. Heat transfers from warmer to cooler places.

4. Metals can reflect radiation or heat.

5. There is no such substance as "coldness."

6. Warm air rises and cooler air sinks.

Table 7 lists the most common scientific conceptions expressed by students in their interviews and describes the number and percentage of students in each interview group who held the conception after the interventions. When compared with Table 4, the scientific conceptions possessed by students prior to the intervention, only one conception remains commonly expressed, the fact that metals can reflect heat or light. Five new conceptions are added at a sufficient frequency while five others are not mentioned at a very much. Overall, it appears that students have equivalent numbers of frequently expressed scientific conceptions about heat and energy after the interventions. The interventions, therefore, did not differ in terms of how they helped students learn and retain scientific conceptions about thermal energy and heat transfer. The values below are presented in terms of frequency and percentage. For example, 4 out of 10 students in the ETK class stated during exit interviews that cold things have heat.
### Table 7

*Scientific conceptions possessed by students after the intervention*

<table>
<thead>
<tr>
<th>Conception</th>
<th>ETK (n = 10)</th>
<th>Control (n = 10)</th>
<th>ETK+D (n = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>frequency</td>
<td>frequency</td>
<td>frequency</td>
</tr>
<tr>
<td>Even cold things have heat</td>
<td>4 (40%)</td>
<td>3 (30%)</td>
<td>2 (20%)</td>
</tr>
<tr>
<td>Heat is from friction/motion</td>
<td>3 (30%)</td>
<td>6 (60%)</td>
<td>7 (70%)</td>
</tr>
<tr>
<td>Heat transfers warm to cool</td>
<td>8 (80%)</td>
<td>8 (80%)</td>
<td>9 (90%)</td>
</tr>
<tr>
<td>Metals reflect radiation or heat</td>
<td>5 (50%)</td>
<td>2 (20%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>There is no “coldness”</td>
<td>4 (40%)</td>
<td>0 (0%)</td>
<td>5 (50%)</td>
</tr>
<tr>
<td>Warm air rises/ cool air sinks</td>
<td>2 (20%)</td>
<td>5 (50%)</td>
<td>3 (30%)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>26</strong></td>
<td><strong>24</strong></td>
<td><strong>26</strong></td>
</tr>
</tbody>
</table>

The most common alternative conceptions stated about heat transfer and temperature during entrance interviews by the students in this study were:

1. Dark objects attract heat
2. Cold transfers from cold to warm places
3. Heat always rises
4. Metals trap or absorb cold
5. Insulators are warm while metal is cold

In Table 8, these alternative conceptions plus ones stated in the exit interviews are tabulated and presented for comparison to Table 5, which can be found on page 172. The frequency of students stating these alternative conceptions dropped by 49% in the ETK class, by 68% in the Control class, and dropped by 69% in the ETK+D class. While scientific conceptions increase equally between classes, alternative conceptions decrease the most in the ETK+D class. The values below are presented in terms of frequency and percentage. For example, 3 out of 10 students in the ETK class stated during exit
interviews that cold things transfers from cold places to warm places.

Table 8

Alternative conceptions possessed by students after the intervention

<table>
<thead>
<tr>
<th>Conception</th>
<th>ETK (n = 10)</th>
<th>Control (n = 10)</th>
<th>ETK+D (n = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold transfers from cold to warm</td>
<td>3 (30%)</td>
<td>4 (40%)</td>
<td>3 (30%)</td>
</tr>
<tr>
<td>Insulators generate heat</td>
<td>1 (10%)</td>
<td>2 (20%)</td>
<td>2 (20%)</td>
</tr>
<tr>
<td>Insulators are warm, metals are cold</td>
<td>4 (40%)</td>
<td>2 (20%)</td>
<td>1 (10%)</td>
</tr>
<tr>
<td>Insulators keep cold from transferring</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Metals trap or absorb cold</td>
<td>2 (20%)</td>
<td>2 (20%)</td>
<td>2 (20%)</td>
</tr>
<tr>
<td>Heat is always warm or hot</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Heat and temperature are equivalent</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Heat always rises</td>
<td>7 (70%)</td>
<td>2 (20%)</td>
<td>2 (20%)</td>
</tr>
<tr>
<td>Dark objects attract heat</td>
<td>4 (40%)</td>
<td>1 (10%)</td>
<td>2 (20%)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>21</strong></td>
<td><strong>13</strong></td>
<td><strong>12</strong></td>
</tr>
</tbody>
</table>

Conceptions in Broad Categories

Six broad categories of conceptions were identified at the beginning of this study:

Heat/Energy, Cold, Insulation, Metals, Radiation, and the Way Things Feel. These categories emerged from entrance interviews with students in all three treatment groups. Prior to the interventions, there was no discernable pattern of alternative and scientific conceptions in these categories. Afterwards, however, a pattern emerged. The values in Table 9 represent the number of different conceptions expressed by students in each broad category in each class. Since the values represent the number of conceptions, not the number of students who stated the conceptions, percentages are not appropriate while the average number of conceptions per student is provided.
Table 9 delineates how students' ideas tended to differentiate between groups with students in the ETK+D class having fewer alternative conceptions and students in the ETK class and ETK+D class having more scientific ones.

<table>
<thead>
<tr>
<th>Category</th>
<th>Scientific Conceptions</th>
<th>Alternative Conceptions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ETK (n=10)</td>
<td>Control (n=10)</td>
</tr>
<tr>
<td></td>
<td>Frequencies</td>
<td>Frequencies</td>
</tr>
<tr>
<td>Heat/Energy</td>
<td>16</td>
<td>22</td>
</tr>
<tr>
<td>Cold</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>Insulation</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Metals</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Radiation</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>Way objects feel</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>51</td>
<td>31</td>
</tr>
<tr>
<td>Avg. per student</td>
<td>5.1</td>
<td>3.1</td>
</tr>
</tbody>
</table>


The most common conceptions stated by students (stated by at least half of students) in all three classes during exit interviews and on the HTE posttest are tabulated in Table 10.

The alternative conceptions are italicized while the scientific ones are not.

Table 10

*Most common scientific and alternative conceptions after intervention.*

<table>
<thead>
<tr>
<th>ETK Class</th>
<th>Control Class</th>
<th>ETK+D Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat transfers warm to cool</td>
<td>Heat is from friction/motion</td>
<td>Heat is from friction/motion</td>
</tr>
<tr>
<td>Metals reflect radiation</td>
<td>Heat transfers warm to cool</td>
<td>Heat transfers warm to cool</td>
</tr>
<tr>
<td><em>Heat rises</em></td>
<td>Warm air rises, cool air sinks</td>
<td>There is no “coldness”</td>
</tr>
<tr>
<td><em>Metal and plastic have different temperatures</em></td>
<td>Metals are conductor</td>
<td>Light colors reflect radiation</td>
</tr>
<tr>
<td>Light colors reflect radiation</td>
<td></td>
<td>Metals are conductors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Insulators prevent heat transfer</td>
</tr>
</tbody>
</table>

Note that students in the ETK+D class have more scientific conceptions than student in the other two classes, and that students in the ETK class have the most alternative conceptions and the least scientific ones.

*Conceptions about thermal energy and heat transfer*

Students in the ETK+D and Control classes stated as many scientific conceptions during their exit interviews as students in the other class. Seven of the 10 students
interviewed in the ETK+D class understood that heat comes from the motion of molecules. Almost all students interviewed in the three classes stated that heat transfers from warmer places to cooler places. A larger difference however occurred in terms of the number of alternative conceptions stated by students during their exit interviews. Students in the ETK+D class students by far stated fewer alternative conceptions about heat and energy than students in the other two classes. The most common alternative conception was that heat rises. Seven out of the 10 students interviewed from the ETK class made this statement in the exit interview whereas only 2 students in the Control class and 2 students in the ETK+D class made this statement.

Stan, a student in the Control class, explained how heat moves from warmer to cooler places, but he still retained a particle theory of heat and a sort of anthropomorphic perception of the "wants" of heat.

Researcher: On the pretest you said the water absorbs energy from the air in the freezer but on the posttest you said the freezer air absorbs heat from the water. Why did you change your mind?

Stan: The freezer air is really cold so the water wants, the heat in the water wants to heat up the cold air, so the freezer just kind of sucks it all up, the energy from the particles.

Researcher: What if the water is just room temperature to start with, does it still have heat in it?

The following interview excerpts are typical of students in all classes pertaining to the statement, "heat rises."

The heat rises from the bottom and goes to the top because the upstairs, I think at the beginning was colder (Casie, exit interview, ETK class).

Heat rises, yeah. Because heat is less dense than regular air so it rises up into the attic (Woody, exit interview, Control class).

We have an upstairs and whenever it's warm, the heat always goes up there. And
it gets really warm upstairs (Beck, exit interview, ETK+D class).

This statement reflects one of the most persistent and common alternative conceptions about heat, used commonly in everyday language (Clough & Driver, 1985; Erickson 1979, 1980). While some students who make this claim might understand that density differences in fluids like water or air cause hotter fluids to float above cooler ones, stating the common phrase is a difficult habit to break.

Conceptions about cold.

Students in the engineering design classes stated more scientific conceptions about cold, and similar numbers of alternative conceptions about cold after the engineering design intervention. They had a better understanding of the concept that “coldness” as a substance does not exist, yet some held onto the idea that cold transfer occurs. The following quotes about “coldness” and the idea of cold transfer are typical of students in the three classes.

Researcher: What did you learn about heat transfer?

Elizabeth: Basically it's like a transfer of energy and the faster particles move, the more heat there's gonna be. And there's no such thing as coldness. It's just how much heat is in something (Elizabeth, ETK 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).

We learned that there is no such thing as cold and so there can't be cold transfer there is only heat transfer so the heat of the counter is transferred to the soda (Sakura, exit interview, ETK+D class).

Some students in each class held onto the concept that cold transfer and cold energy exist. This is surprising considering the opportunities they had to un-learn this
tenacious conception. Callie, a student in the Control class, explained her correct answer to this question in the exit interview by stating that heat moves out of the cooling egg.

The egg is hotter, and the water is colder, so the egg is going, the egg's heat is going out of, out into the water, and the water isn't making it colder—but the heat in the egg is releasing it, so it just gets colder (Callie, exit interview, Control class).

Julie, a student in the ETK+D class, explained her correct answer to this question in the exit interview by explaining that heat moves from warmer places to cooler places.

I realized that there was really no such thing as coldness and that thermal energy travels from a warmer place to a cooler place instead of the other way around. (Julie, ETK+D class, exit interview)

Conceptions about insulators.

Students in the ETK class expressed more scientific conceptions about insulators after the treatment than students in the other two classes. Students with the engineering design treatment outperformed students without the engineering design treatment in terms of making correct statements about insulators. These students showed a definite improvement in understanding that air is a good insulator when compared to their entrance interviews. Incorrect statements about insulators were rare during the exit interviews.

The only alternative conception stated about insulators during the exit interviews was that insulating material makes things warm, whether it be sweaters or other thick materials. Excerpts from exit interviews expand upon students' thinking.

Most of the scientific conceptions about insulators stated during exit interviews came from students in the ETK class, while very few students had many alternative
conceptions about insulators after the interventions.

Elizabeth in the ETK class was asked to explain why she thought aluminum foil would be the best choice for keeping a can of soda cold, and she explained that sweaters make things warm.

Researcher: You chose aluminum foil. Why?
Elizabeth: Because aluminum foil is a conductor so it would keep the energy of the soda together and it wouldn't just radiate away, or like escape.
Researcher: Why do you think the other answers would not work as well?
Elizabeth: Wool sweater is an insulator, so I think that would make it warm.

Elizabeth’s answer indicated that she still perceived insulators as materials that actually make things warm as if they have heat-generating properties.

Jim (Control class) explained his reasoning for choosing a paper towel instead of wool to keep a can of soda cold, reflecting his lack of understanding about the difference between insulators and conductors.

Researcher: Why did you choose the paper towel?
Jim (Control class): Wool, I think would make it kind of hot, I think. It's like if you wear wool on a cold day, it will keep you warm because it's a conductor.

Conceptions about metals.

Students in the engineering design classes had slightly more scientific conceptions about metals and their relationship to heat after the intervention. No students in the ETK+D class stated alternative conceptions about metals in their exit interviews whereas they had equivalent numbers of alternative conceptions about metals prior to the intervention.
Alternative conceptions about metals and their relationship to heat and thermal energy still existed after the interventions, but to a lesser degree. Only 2 students in each class articulated an alternative conception about metals in the exit interviews. Some sample quotes from students during their exit interviews which illustrate students' remaining alternative conceptions about metals follow:

- I think that metal just like attracts coldness more than wood (Jenny, ETK class, exit interview).
- The coldness will go into the aluminum foil and it will stay there (Callie, Control class, exit interview).
- I would sit on the wooden bench because the metal one, it conducts the heat around it, it's might be burning hot if it's really sunny out or it might be freezing cold if it's really cold out, so it changes when the seasons change, and so if it's winter then it absorbs the cold and if it's summer it absorbs the heat (Callie, Control class, exit interview).

**Conceptions about radiation.**

Students in the engineering design classes expressed many scientific conceptions about radiation during their exit interviews. They stated that Mylar reflects radiation, that hot objects emit radiation, and that light emits radiation. Perhaps this is because they had more opportunities to discuss radiation in relationship to their dwelling designs. However, this also gave them more opportunities to state alternative conceptions, which they did to some degree. Two students retained the notion that black objects “attract” radiation instead of “absorb” radiation.

Students in the ETK+D class discussed Mylar and how it reflects radiation because they used it to build their dwellings. Students in the ETK class discussed how
light emits radiation as they discussed how their dwelling would be put under a heat lamp. Typical statements from students in these two classes follow:

Researcher: So what did you do to keep radiation out?
Tommy (ETK class): We thought it was the Mylar, which I don't think worked very well.

We used the (Mylar) space blanket to cover the top because it would reflect the radiation coming from the heat lamps (Julie, ETK+D class, exit interview).

The space blanket reflects the light and we have really good insulators in here-air, plastic, cotton, and the bottom is white because it doesn’t absorb as much heat (Samantha, ETK+D class, exit interview).

Students in the ETK class also had more to say about black “attracting” heat, most likely because they had experience with the black bottom of the hot box which was used to test their dwellings. Excerpts from their exit interviews follow. Jenny and Sarah, who worked as a team, each explain why they decided to make a black extension to their dwelling in order to “attract the light away” from the ice cube.

We decided on this little black house thing because of the whole blackness around it. We thought the light would be more attracted over there (Jenny, exit interview, ETK class).

So we had these black sides... and so what we were trying to do was we were trying to get, like, more of the heat, more of the lamp to go to the black instead of our penguin (Sarah, exit interview, ETK class).

They believed that if they made a black box next to their penguin dwelling, that the box would attract the light and keep it away from their ice cube. On their second design iteration, these two modified their design substantially. See Figure 14 for the before and after dwellings.
First and second design iteration for Sarah and Jenny in class ETK.

No longer did the black box serve as a decoy- instead it became a base to elevate the insulated penguin. Instead of only 3.9 grams of ice remaining after the first iteration, 6.0 grams remained after modifying the black box.

*Conceptions about how objects feel.*

Many students’ perceptions of heat transfer came from how objects feel. Over the course of this intervention, students demonstrated fewer alternative conceptions about the relationship between heat and how objects feel to them. A few students in the engineering design classes stated that while metals felt colder than plastics, things can feel differently yet have the same temperature. However, some students also held onto their alternative conceptions that conductors and insulators in the same environment actually have different temperatures. Sakura in the ETK+D class explained her alternative conception that wood does not become as cold as metal.

Metal would be affected by the cold air so the metal will transfer its heat to the air
and become cold, as cold as the air, but wood basically keeps its temperature. So it will be warmer than the metal (Sakura, exit interview, ETK+D class).

Kate, a student in the ETK class, was asked in the exit interview whether she would prefer to sit on a metal bench or a wooden bench in the wintertime. She responded in a way that was typical of the other three students in her class who made this statement.

Kate (ETK class): Mmmm… the wooden bench because, um, metal bench is a conductor.
Researcher: What's wrong with that?
Kate: Because it would be really cold because it doesn’t hold in heat as well as heat because wood's an insulator.
Researcher: So, you would feel different sitting on it?
Kate: It wouldn't be as cold as the metal.
Researcher: So if you could take the temperatures of the two of them, do you think one would be warmer than the other?
Kate: Yeah, the wooden one.

Although the teacher talked about this concept in all three classes, and although students in the ETK+D class experienced a demonstration that specifically targeted this conception, students' reliance on their sense of touch dominated, and this abstract concept did not fully congeal in their minds. Question 11 on the HTE specifically addressed this concept, and while exit interviews did not completely tease out the differences, no students in the ETK class correctly answered the question which asked if a metal and plastic tray would have the same temperature in a freezer. Over one-third of students in the Control class and the ETK+D class correctly stated that the two trays would have the same temperature- but two-thirds did not.
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 targeted demonstrations made more gains in most areas of the science of 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 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.

When compared with the list of alternative conceptions that students articulated during entrance interviews (Table 5), each class made positive gains in reducing the number of alternative conceptions held about heat and energy. Students in the ETK+D class articulated the fewest number of alternative conceptions after the intervention, while students in the ETK class demonstrated the greatest number of alternative conceptions after intervention.

Some students still held onto the notion that cold transfers, that heat rises, that insulators are warm and generate heat, and that metals trap coldness. However, students developed a better understanding about the nature of heat, how it differs from temperature, insulation, and the relationship between the color of an object and the radiation it absorbs.
Summary of Research Question #1

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 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 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 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. 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.

Engineering Attitudes and Understanding

Research Question #2: How might students’ conceptions about and attitudes toward engineering differ before, during, and after learning heat transfer and thermal energy through an engineering design challenge?

One goal in using engineering design in science classrooms is to expose students to engineering as a career, teach them what engineers do for a living, and help them understand the impact engineers have on their everyday lives. Prior to the intervention, students from all three classes were administered the Attitudes toward Engineering...
Survey (ATES) (Appendix G) in order to determine their baseline attitude toward engineers and engineering as a career.

Students ranked 11 items on a scale of 1 to 5 from “Strongly disagree” to “Strongly agree” on items such as “Engineering would be a highly interesting profession for me” and “Engineering is important to our country’s economic success in the world.” Values for questions with negative statements about engineering, like “Engineers don’t need to know much about environmental issues” were reversed so that a score of 5 (strongly agree) would equal an attitudinal score of 1. Scores from students in the three classes were corrected to measure positive attitudes, then 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.

Assertion 4: Students’ attitudes toward and understanding of engineering were similar across all three groups prior to instruction.

ATES Pretests

All students took the Attitude toward Engineering Survey (ATES) prior to and after the intervention. The ETK class, with $n = 21$ students, obtained a mean attitudinal score of 3.35 ($SD=.45$) out of 5 points on the Likert scale ATES. The Control class, with $n = 27$ students, obtained a mean attitudinal score of 3.52 ($SD=.45$). The ETK+D class, with $n = 23$ students, obtained a mean attitudinal score of 3.64 ($SD=.46$). These scores were slightly better than the Likert scale value 3, which indicated a neutral attitude. It
was expected that students would score around the neutral middle of the scale. Scores were normally distributed for each class; for Shapiro-Wilk’s test of normality, significance ranged from .155 to .957. The variances were homogeneous as tested with Levene’s statistic, $p = .953$. 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. A one-way 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 $r = .18$.

Table 11 illustrates the raw values students from each class gave each item on the engineering attitudes pretest. These values have not been reversed for negative statements. For example, the mean value for Item 6, “Engineers don’t need to know much about environmental issues” was under 3.0. This actually indicated a positive attitude toward engineering, so for each student, the value was reversed (a 2 was changed to a 4) in the statistical analysis so all values measured positive attitudes. Refer to Appendix G for the questions.
Table 11
*Pretest: Attitudes toward Engineering Survey*

<table>
<thead>
<tr>
<th>Question</th>
<th>ETK class (n = 21)</th>
<th>Control class (n = 27)</th>
<th>ETK+D class (n = 23)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.67</td>
<td>3.26</td>
<td>3.39</td>
</tr>
<tr>
<td>2</td>
<td>3.62</td>
<td>3.26</td>
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<td>3</td>
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<tr>
<td>6</td>
<td>2.33</td>
<td>2.04</td>
<td>1.70</td>
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<tr>
<td>7</td>
<td>2.76</td>
<td>2.48</td>
<td>2.22</td>
</tr>
<tr>
<td>8</td>
<td>3.67</td>
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<tr>
<td>10</td>
<td>2.71</td>
<td>2.89</td>
<td>2.83</td>
</tr>
<tr>
<td>11</td>
<td>2.71</td>
<td>2.48</td>
<td>2.39</td>
</tr>
</tbody>
</table>

The students in all three classes (Question 3) 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 (Question 5). Overall, the differences as a whole were not significant between classes.

*Entrance Interviews*

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. The following quotes are typical from entrance interviews with students in each class in that each represents common misconceptions about engineering. They are responses to the question, “Do you know anyone who is an engineer?”

Researcher: Do you know what engineering is?
Kate (ETK class): No. Not exactly.
Researcher: Do you have any idea what an engineer’s job would be?
Kate: Like driving a train?
Researcher: What kinds of people do you think grow up to be engineers?
Kate: Ones who like driving trains.

Researcher: What would you describe an engineer’s job is like?
Casie (ETK class): Working on cars or things with motors. Stuff like that. Learning how to fix them and make them.

Researcher: Do you have any idea, what an engineer might do for a living?
Woody (Control class): Fix cars.
Researcher: Any other things engineers might do?
ATES Posttest

Assertion 5: Students’ attitudes toward engineering changed during the design intervention when they were exposed to engineering design.

Students in all classes took the Attitude toward Engineering Survey (ATES) prior to and after the intervention. Two of the three classes were exposed to an engineering design challenge. Students in these two groups had a positive change in attitudes toward engineering on the Attitudes toward Engineering Survey. Table 12 illustrates the raw values students from each class gave each question on the engineering attitudes posttest. Once again, these values have not been reversed for negative statements. One student in the study did not take the ATES posttest, so her score was computed using the equation from Tabachnick & Fidell (2001, p. 430):

\[ Y_{ij} = \frac{(sS_i + aA_j - B)}{(a-1)(s-1)} \]

This equation imputes the missing value, taking into account the class and the individual.

- \( s \) = the number of students in the class
- \( S_i \) = the sum of the student’s scores on engineering attitudes (pretest score)
- \( a \) = the number of levels for engineering attitudes (two: pre and post)
- \( A_j \) = the sum of all students’ scores in the class at that level (posttest scores)
- \( B \) = the sum of all students’ scores in the class at all levels (pre and posttest)
In order to see changes for each question in each class, see Table 13. It represents the differences between posttest and pretest scores. A positive value indicates an increase in the score from pre- to posttest, however this does not indicate a positive increase in attitude since these are raw scores and some items are negative statements, like Question 6, “Engineers don’t need to know much about environmental issues.”

Results from the ATES survey are mixed, and alone do not reveal significant differences between classes in terms of changes in attitude. For example, there was very little change in the two design classes for Item 1, “Engineering would be a highly interesting profession for me.” There was a moderate change in both engineering design classes on Item 2, “Engineers spend most of their time doing complex mathematical calculations” with little change in the Control Class. Ironically, there was no change in the ETK+D class on Item 6, “Engineers don’t need to know much about environmental
issues.” There was a moderate positive change for both engineering classes on Item 8, “Engineering skills are useful in everyday life” but no change for the Control Class. Students in the ETK+D class, however, had an increased interest in a career in engineering over students in the other two classes as indicated by results from Item 9, “I would consider a career in engineering.” This is not consistent with results from Item 1, so perhaps while students in the ETK+D class did not find engineering any more interesting than they did prior to the intervention, they did have an increased interest in pursuing it as a career for other reasons.

Table 13
Pre-Posttest Changes: Attitudes toward Engineering Survey

<table>
<thead>
<tr>
<th>Question</th>
<th>ETK class (n = 21)</th>
<th>Control class (n = 27)</th>
<th>ETK+D class (n = 23)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00</td>
<td>-0.22</td>
<td>-0.01</td>
</tr>
<tr>
<td>2</td>
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</tr>
<tr>
<td>4</td>
<td>-0.19</td>
<td>-0.45</td>
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<tr>
<td>5</td>
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<td>0.26</td>
<td>0.26</td>
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<td>6</td>
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<tr>
<td>7</td>
<td>-0.24</td>
<td>-0.22</td>
<td>-0.26</td>
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<tr>
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</tr>
<tr>
<td>11</td>
<td>-0.47</td>
<td>0.08</td>
<td>-0.03</td>
</tr>
</tbody>
</table>

Paired t-tests were used to compare pre- and posttests scores for each class. Since three different tests were performed, the level of significance was reduced in order to reduce the Type I error rate. Therefore, significance is defined as less than .05/3 = .0167. 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 with $t(20) = 3.739, p = .001$ 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 $r = .26$. See Figure 15 for the graph showing 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 ANCOVA, the overall difference was not significant between classes. $F(2,67) = 2.055, p = .136$ and pairwise comparisons did not reveal any differences between classes.
Figure 15. Means for all three classes: Pretest and posttest scores on ATES

The very small difference in attitudes toward engineering in the Control class could have occurred 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, the changes were significant. Whereas the 11-item ATES did not discriminate between classes in terms of engineering attitudes, interviews with students did a better job of finding out what students were thinking about engineering in a broad sense.
Exit Interviews

In the exit interviews, engineering design students in the ETK class and the ETK+D class had the most accurate conceptions about engineering. Conception maps illustrated by figures 16 and 18 were generated by the researcher in order to illustrate the statements students made in these two classes during their exit interviews after the design intervention. Statements about engineering were collected and then grouped according to similarities. Students in the Control class mentioned several functions of engineering, but three primary functions were “building cars”, “fixing cars”, and “working on cars.”

![Diagram of engineering conceptions](image)

Figure 16. The ETK class students’ conceptions of what engineers do after the design intervention

The differences between the classes that received the engineering design intervention and the class that did not are apparent in that students in the design classes...
had more sophisticated and complete ideas about the functions of engineers than students in the Control class (see Figure 17). Part of the analysis of qualitative interview data involved creating and comparing these conception maps.

![Diagram](image)

**Figure 17.** The Control class students' conceptions of what engineers do after the design intervention.

Students in the ETK+D class stated rich descriptions of what engineers do after the design-based intervention, including such things as brainstorming, working with chemicals, troubleshooting, researching things, and making things better. See Figure 18. Conversely, students in the Control class had the same "engine-based" conceptions after the unit.
Changes on the ATES mirror what students had to say about engineering after the interventions, as illustrated in the concept maps in Figures 16, 17, and 18.

The following excerpts from exit interviews show the typical changes students had in terms of what they perceived that engineers do.

In the ETK class, Jenny thought perhaps an engineer was the same thing as a car mechanic prior to the engineering intervention. She said that engineers worked with their hands to build things and had to be good at math. After the intervention, she said that engineers build stuff, make new products, make contraptions, and fix things. While Kate thought that engineers drove trains prior to the intervention, afterwards she said engineers are interesting, work-savvy people who design or build different things like iPods.
In the Control class, Jim said he did not know any engineers during the entrance interview, but that he thought they made or designed buildings. During the exit interview, Jim’s conception of engineering did not change. He stated that engineers build food stores or buildings and has no interest in it as a career. Woody said that engineers fix cars, automobiles, airplanes, and mechanical things. After the intervention he said he might want to be an engineer because he likes fixing cars. Molly scored the lowest in the Control class on the Survey of Attitudes toward Engineering. She said that she thought she knew an engineer who built guitars for a living. During the exit interview, Molly had an increased understanding of engineering. She stated that they fix cars, fix copy machines when they break, and figure out how things work.

In the ETK+D class, Robbie said during the entrance interview that engineers use math and science to build things like cars and planes and trains. He said that they like math and science, are determined people, and that he had a little bit of interest in engineering. During his exit interview he said that engineers are “every day superheroes” who make economically friendly and environmentally friendly items that help people. Ed scored the highest his class on the Attitude toward Engineering Survey pretest with a score of 4.82 out of 5. He said in his entrance interview that engineers design or build things that reduce pollution. On his posttest, he scored the highest out of all three classes with a 4.91. He said in his exit interview that engineers design, build, brainstorm, troubleshoot, test things, get funding, and can fix anything. Dara did not know any engineers prior to the design intervention. She said that engineers like to experiment, love science, and figure out things. Her engineering attitudes posttest score was the highest
amongst all the girls in the study. She said that engineers want to make things better. She said, "I have no idea what I want to be and I was just thinking that engineering could be a choice right there. I like math. I like science. Engineering! I could be doing this one day (Dara, exit interview, The ETK+D class).

Assertion 6: Female students' attitudes toward engineering changed during the design intervention when they were exposed to engineering design whereas male students' attitudes did not.

In addition to the overall analysis of engineering attitude changes, gender was used as an independent variable to determine whether males and females differed in their attitudes. 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.

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 at least than $0.05/3 = .0167$) 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 \( r = .16 \). See Figure 19.

Figure 19. 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 at least 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 \( r = .32 \). See Figure 20.
Figure 20. Female students' attitudes toward engineering

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 pretest score on the ATES. Male students also ended up with a higher posttest scores on the ATES in the engineering-based classes, but the change over time was not significant. The combination of the design challenge and the targeted demonstrations was especially effective in promoting female students' attitudes toward engineering.

Summary of Research Question #2

Learning science through an engineering design activity had a positive effect on students' attitudes toward and knowledge about engineering. Male and female students in
the design classes reported knowing more accurate facts about what engineers do for a living. Students in the Control class did not have significant changes overall in terms of knowledge about engineering or increased attitudes toward engineering. Female students in the engineering classes had significant changes pre- to posttest on the ATES while male students did not. Perhaps several factors can account for that difference, one being the female-friendly design activity which was set in the context of helping people and animals. It did not require any prior knowledge about mechanics or construction techniques. In Chapter 5 this issue of a possible gender effect will be discussed in more detail.

The Impact of Engineering Design on Science Concept Knowledge

Research Question #3: How might an engineering design challenge specifically change students' conceptions of thermal energy and heat transfer?

This question was answered through evidence from classroom discussions, observations, artifacts, and interviews with students after the design challenge. Through a close and careful analysis of how students discussed heat transfer and thermal energy, and an examination of the context in which these discussions happened, it was possible to come to a tentative conclusion. 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. Although a small sample size of eight designs in the class prohibited statistical tests from detecting statistically significant relationships between design success and science conceptual change, there appeared to be a positive correlation in the ETK+D class between the two measures. Student groups who designed better dwellings that preserved more ice, performed higher on the HTE posttest. Only future research with larger sample sizes can confirm this inference.

Assertion 7: Students' understandings about heat transfer were positively affected by all three treatments, but more so when they were exposed to the engineering design activity and targeted demonstrations.

Evidence from Classroom Discussions, Observations, and Interviews.

Students in the ETK class used scientific terms while testing materials, designing, and building their penguin dwelling. They talked about insulators and conductors, radiation, conduction, and convection. They applied what they had learned from their testing toward their dwelling design. They analyzed different materials for ways each one would prevent some sort of heat transfer. However, they did not all use scientific terms correctly. Some students still talked about keeping the “cold” inside the penguin dwelling, or using materials that did not “attract” the heat. Marlene worked with a group of three other female students. They actually won the competition in their class although they did not have a scientifically complete rationale for their design. It was as if the science and the design were working against each other. Given a choice to focus on the
science content or the design challenge, students in the ETK class seemed to focus on the design challenge. This is confirmed by their lower HTE posttest scores, and the negative correlation between their success at keeping the ice cube from melting and their HTE posttest scores. With a small sample size of only eight student groups, significance could not be reached with this correlation, but it appeared that 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.

Marlene, a student in the winning team in the ETK class, was certainly focusing on the design as she spoke with her teammates during construction. However, her scientific explanation was incorrect.

First is the space blanket and were going to put it really tight so that the cold comes up and reflects back in. And we're going to put bubble wrap over it because it will keep in the coldness in even more. And then, the space blanket is reflecting the coldness back into the penguin. (Marlene, classroom discourse day 4, ETK class)

Some student groups in the ETK class did a better job of applying the science to the design task. Daniel was very analytical and did a good job applying his knowledge of heat transfer to the engineering design. In his exit interview he said, “If you don’t know how to apply your knowledge, the knowledge is basically useless except on Jeopardy. I’m more likely to remember the penguin experiment than the notes.” In analyzing his group’s design, he said during his exit interview:

Daniel: I think we probably should have changed where the penguin was. It was a bit too compact, maybe. If we had insulation, air is a good insulator.
Researcher: So you needed more insulation. I see you have lots of layers here.

Daniel: But they're pretty close together. And we should have covered the sides. We raised it and we put a shade over it, but probably convection hurt us.

On day 4 of the treatment, Daniel's group was discussing their design, and it was obvious that they were skilled at applying their new knowledge to the task, and doing so methodically:

Margaret: I think we've done enough tests. We need to start figuring out what are going to build.

Reggie: Use bubble wrap, because it has a lot of air in it.

Margaret: It's an insulator.

Reggie: We should have space blanket or aluminum foil to reflect the radiation. We need a base that's an insulator. We shouldn't buy it until we're done with tests.

Elizabeth in the ETK class also seemed to do well applying science to her design. In her exit interview she described her design, using appropriate terminology effectively. She described how she used materials to reflect radiation, reduce convection currents, and guard against conduction with the black base of the test oven.

Well, we put aluminum on the top because we thought that was going to get the heat away from it when we tested it. And then we put the bubble paper inside to keep the heat from getting inside and then another piece of paper. And then we did a few pieces of bubble paper and cut a place for the penguin where it would lay, so that when we closed it up he would be embedded in there, and then he could be closed in and heat wouldn't get in. And then we put paper on the ground so that he would not be on the black ground. And we changed it by putting legs on it so that it would be off the ground even more, and we put something so that something could drape over it to keep the radiation out even more. (Elizabeth, exit interview, ETK class)

Students in the ETK+D class not only applied their knowledge about heat transfer to the design and construction of the dwelling, but also at times, they applied what they had learned from the targeted demonstrations. The following excerpt from Dara's exit
interview highlights how the demonstration with the six soda cans wrapped in different materials affected her decision to use cotton balls as insulation.

Researcher: What do you think was a really good design decision that you made on your house?

Dara (ETK+D class): Cotton balls. Because cotton balls, as we did with the soda can, the sock was a good insulator so I think that with the cotton balls surrounding the penguin, it was trapping the air so it wasn’t letting a lot get out and wasn’t letting a lot get in. I think that the cotton balls were a very good choice.

Researcher: What activities contributed to your decisions in building the house the way you built it?

Student: The soda cans with these six soda cans, I thought that made a humungo part.

Beck (ETK+D class) stated in his exit interview that the house demonstration helped him with design decisions. The demonstration where a student felt the heat coming from the heat lamp with his hand, and then felt the heat being blocked immediately when a piece of Mylar was placed in-between the hand and the lamp, was influential in teaching him about the radiation reflection properties of that substance.

The teacher did a good job in both classes discussing tentative results with the class as a whole, encouraging students to share their knowledge and not treat the exercise like a competition with coveted information. This excerpt is from the ETK+D class on day 4 of the treatment. It highlights how the teacher solicited ideas from the class, allowing them to share their ideas about blocking radiation, convection, and conduction.

Teacher: Based on the results you see, what are some things that are good at reflection of radiation?

Ward: The space blanket

Teacher: What else helped with radiation?

Jack: aluminum
Zack: foam
Dara: I thought felt helped.
Teacher: What do you think was an insulator?
Bonnie: Wood
Dara: Cotton balls
Teacher: Is there going to be convection happening?
Students: Yes.
Teacher: What are some things you can do to help combat convection?
Ed: Keep it airtight.

Julie, also in the ETK+D class, shared in her exit interview how she learned that the black floor of the hot box was radiating heat upwards toward the dwellings, and how she planned to try and stop that radiation from entering her dwelling.

We used the space blanket to cover the top because it would reflect the radiation coming from the heat lamps. The bottom of the container was black. There was a lot of energy in it already so we thought if we used a color like white it would help reflect some of the rays. We were thinking the bubble wrap didn’t really do a good job so we were thinking about taking that out and also we were thinking about elevating it so it wouldn’t come in direct contact with the bottom. And also putting some space blanket because we just realized that there were energy rays at the bottom coming up too. So, we were going to put some space blanket to reflect that. (Julie, ETK+D class, exit interview)

Students were able to get the greatest benefit from the engineering design activity when their understandings about heat transfer were addressed conceptually from the beginning, and when scaffolding was provided to help students re-build their conceptions of heat transfer. The design process and acquisition of scientifically correct conceptions did not compete with each other. They were mutually supportive.

Summary of Research Question 3

Evidence from both quantitative and qualitative data suggests that exposure to
engineering design activities helps students conceptualize science content. Certainly 
qualitative data exist to support this hypothesis, but also analysis of data from the Heat 
Transfer Evaluation and the Attitudes toward Engineering Survey suggests this 
relationship to be accurate. What can be stated with certainty from this study is that 
ingineering design activities promote a more positive attitude toward engineering and 
greater understandings about engineering as a career. Students exposed to both 
ingineering design activities and demonstrations targeting alternative conceptions 
outperformed students exposed to typical instruction and students exposed to the 
ingineering design activities alone. Interview data supports the assertion that learning the 
science content positively correlates with attitudes toward engineering. While students in 
the Control class did indeed make positive and statistically significant changes in 
knowledge about heat transfer, they did not make significantly positive changes in 
attitudes toward engineering. Other factors, therefore, contributed toward their 
knowledge growth. The fact that students in the ETK+D class made the largest change 
overall in knowledge about heat transfer and a significant change on the ATES in 
attitudes toward engineering also supports the tentative assertion that increased attitudes 
toward engineering through engineering design activities positively affects concept 
knowledge outcomes in a design-based treatment. Additional data supports the tentative 
finding that students whose alternative conceptions were addressed were able to also 
perform better on the design challenge. This suggests that the science concepts, when 
addressed from an alternative conceptions stance, allowed students to perform better on 
ingineering design activities.
CHAPTER V: DISCUSSION AND IMPLICATIONS

Introduction

This study focused on engineering design in the middle school science classroom, and examined one way that conceptual change in science could be fostered through a combination of design activities and demonstrations targeting research-based alternative conceptions. Engineering design has been shown to be effective in science classrooms to some degree, but it is not clear from previous studies whether students learning science through engineering design are better off than students who learn in traditional classrooms (Fortus et al., 2004; LaChapelle & Cunningham, 2007). In this thesis, the results from three classes studying the science of heat transfer and thermal energy through typical and engineering-design-based curricula were presented and compared, effectively assessing the argument for the use of engineering design activities in science education at the middle school level.

Results from this study indicated that student attitudes toward and understandings about engineering increased as a result of an engineering-design-based curricula; however, female students' attitudes increased more than male students. Additionally, student understandings of thermal energy and heat transfer increased in all three treatment groups; however students who were taught through both engineering design
activities and demonstrations designed to target alternative conceptions about heat made
greater advances in understandings than students in the other classes.

This chapter not only explicates the findings reported in Chapter IV, but it situates these findings within, and compares them to, previous research on engineering design interventions. The discussion is described in six sections. The first section examines students' conceptions about the science of heat transfer and thermal energy in light of previous research into children's alternative conceptions about heat and energy. The second section explores the demonstrations added to the engineering curriculum in terms of their impact on conceptual change and examines how they may have lead to greater gains in science learning. The third section explores the attitudes and behaviors of the middle school teacher used in this study, and the fourth section examines the differences in gender, especially differences in attitude toward engineering between the male and female participants in this study. Finally, the limitations of the study are presented in the fifth section while recommendations for future research are described in the final section.

Students' Conceptions of Thermal Energy and Heat Transfer

The terms, "heat" and "temperature" are so very common in our everyday vocabulary that students often come to school at an early age with conceptions already formed about what these concepts mean (Albert, 1978; Clough & Driver, 1995; Erickson, 1979, 1980; Paik et al., 2007). Unfortunately, these conceptions are most often incorrect, and tend to mirror the 18th century caloric theory of heat. Students think of heat as a substance that flows or is made of "heat particles", think of cold as the opposite of heat, and think of cold as something that flows as well. The true, scientific conceptions of heat,
thermal energy, and temperature are often even misunderstood by senior level mechanical and chemical engineering students after specifically completing coursework in thermodynamics and heat transfer (Miller et al., 2006). If alternative conceptions are not addressed in school and if students do not experience ways to change or discard them, they will persist into adulthood, even in adults who have had explicit instruction in these areas of science (Lewis & Linn, 2003).

A confounding problem with understanding heat and temperature is that students use their senses to define these terms, and human senses can be deceiving. When students touch a metal tray and a plastic tray, they will state that the metal one not only feels colder, it is colder. They think of heat as always being hot, and use terms like “body heat” and “steaming hot” and “icy cold” with a sense of knowing. They are using their common sense, yet, they do not understand kinetic theory, do not know the difference between heat and thermal energy, do not understand the directionality of heat transfer, and insist that when something feels cold to them, the “coldness” is transferring TO their bodies. We are surrounded by experiences with heat and temperature and thermal energy. This familiarity with the concepts breeds alternative conceptions (Colburn, 2009).

Entrance interviews and pre-assessments were used in this study to determine students’ alternative conceptions about heat transfer and thermal energy. After all students’ alternative conceptions were elucidated, they were sorted and collapsed into a manageable set of distinct concepts.

1. Cold transfers in order to make things cold or make them freeze
2. Wood and plastic are warmer than metal
3. Cold is a substance
4. Metals trap or absorb cold
5. Heat is something that is always warm or hot
6. Sweaters, blankets, and socks generate heat
7. Heat always rises
8. Dark objects attract heat

All of these conceptions, or variations of them, were identified in previous studies of children ages 4-11 (Albert, 1978; Paik et al., 2007), ages 12 to 16 (Clough & Driver, 1985; Erickson, 1979; Erickson, 1980), and even adults ages 19 - 45 (Lewis & Linn, 2003). Paik, Cho, and Go (2007) discovered that the number of alternative conceptions children have about heat transfer may actually increase as they progress through school from age 4 to 11. They postulated that alternative conceptions may actually be formed at school during science classes.

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. After the intervention, this relatively homogeneous representation of ideas changed. As demonstrated by exit interviews with students in each class, students in the ETK class had fewer, but just as many alternative conceptions as students in the Control class. 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.

_Engineering Design Alone is not Enough_

Of the three classes participating in this study, the classes that demonstrated the least amount of conceptual change in the areas of heat transfer and thermal energy were the ETK class and the Control class. As reviewed in Chapter 2, 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). The Learning by Design group at Georgia Tech specifically recommended that a structure of some sort is needed to bridge the gap between an engineering design problem and the science content which supports it; they suggested computer tools and design diaries (Puntambekar & Kolodner, 2005). In this study, demonstrations specifically designed to target typical alternative conceptions were used to provide that structure for students in the ETK+D class. For example, students were directly confronted with their alternative conception that metal insulates and traps “cold” through a demonstration with a series of cold soda cans wrapped in a variety of materials. The can wrapped in the wool sock stayed cold the longest, provoking students to consider heat transfer in a different light. Students insisted that metal is colder than plastic until two demonstrations using plastic and metal spoons, and plastic and metal trays showed them that plastic merely slows heat transfer, thus feels warmer to the touch. This study is unique in that no studies using this engineering design/alternative conceptions approach could be found in the literature.

In order for engineering design activities to be more successful in both improving students’ science concepts and their engineering attitudes and knowledge, alternative
conceptions need to be addressed. Learning is a process of conceptual change, and a learner needs to recognize his alternative conceptions, become dissatisfied with them, and then find new scientific conceptions plausible before they are assimilated and accommodated (Posner, Strike, Hewson, & Gertzog, 1982). This study demonstrated that a set of five targeted demonstrations that took a total of one class period to complete may be the key to helping students better learn science through engineering design, and design well as engineers. Without addressing alternative conceptions, students doing engineering design learned about engineering and gained better attitudes toward it, but did not increase their knowledge about heat transfer to the same degree as students in the other classes even though they were successful designers. These results are similar to 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 Fills a Gap in the Literature

The findings in this study fill a gap in the literature and lend support to the argument that engineering design alone helps students identify, desire to change, and modify their alternative conceptions about science. However, when engineering design is combined with demonstrations and activities targeted at alternative conceptions, this learning occurs to a greater degree. With dozens of engineering design-based curricular materials being sold or freely disseminated, this finding should be taken seriously if the desired outcomes of engineering design activities involve the S, the T, and the E from the acronym, STEM (Science, Technology, Engineering, and Mathematics):
The methodology of this study fills the gap in that only two of the studies described in Chapter 2 addressed scientific knowledge and used a control group for comparison. Hmelo et al. (2000) found that Learning by Design students made significant changes from pre- to posttest on an assessment of lung function, whereas the control group students did not. However, students in the control group had a different teacher than students in the experimental group, and there is no report on what the teacher effect might have been, or whether both groups were even taught with the same objectives.

Lachapelle and Cunningham (2007) used a large sample of elementary students in six states to evaluate the Engineering is Elementary curriculum. While they used a control group, students in that group were a) all in one state, b) of lower socioeconomic status, and c) more often English Language Learners. Only one science question was shared between the control and experimental group, and both groups made significant gains pre- to posttest on this question about condensation.

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 intervention 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 results of this study indicate that a middle school teacher with very little prior knowledge about engineering can successfully conduct an engineering design activity with her students. Although the researcher in this study provided a mentor-type role and was committed to her success, this role was not the primary goal; after initial teacher training, the researcher took on a more observational and less instructive role. Without a researcher/mentor in the classroom the teacher might have struggled more with the curriculum, but this cannot be known. The teacher was not heavily reliant on the researcher for advice and support, so she likely would have been as successful or almost as successful without the mentor presence. The curriculum was written with enough detail that a teacher without any mentoring would likely be successful as well.

The language of design is not fluent in novice teachers as they struggle with the processes, and it comes more naturally to expert designers (Heylighten, Bouwen, & Neuckermans, 1999). Prior to this study, the classroom teacher stated in her entrance interview that she had never even met an engineer. In this sense, she is a novice teacher of engineering design. Her introduction to engineering occurred as she prepared for the ETK and read over the notes in the “Introduction to Engineering” PowerPoint. She felt competent talking about engineering, but admitted that it was not her strength. She had used design activities in her physical science class the year before, but never explicitly tied these design activities to engineering. Her rationale for using design activities in the past was clear; she strongly felt that designing artifacts made science more real to students.
When you’re designing something, you’re thinking about it, you’re being
creative, you brainstorm. Usually when you’re designing you’re usually designing
with other people or you’re bouncing your ideas off. They really learn a lot and
then when they’re actually having to make it, it’s a whole different ballgame. I
think it really, really comes full circle, really lets them learn in full. (Ms. Smith,
Entrance interview)

In previous studies which involved teachers who were new to engineering design-based
curriculum, engineering was not mentioned (McRobbie et al., 2000; Hmelo et al., 2000;
Mehalik et al., 2008). The activities in these studies were engineering design activities,
but they were couched in a “design” framework, not an “engineering” one. This may
have helped teachers to not feel intimidated by the curriculum. “Design” is a term that
artists, architects, landscape designers, interior designers, fashion designers, and even
hair-style designers use. It is a creative process, but one that does not necessarily rely on
scientific or mathematical principles. None of the students in these studies were assessed
on their attitudes toward engineering, which likely would not have changed anyway
because engineering was not stressed; design was.

Considering the limitations this middle school teacher had in terms of knowledge
about engineering, using this ETK and the targeted demonstrations with her classes for
the first time, and some misconceptions she had about heat and energy herself prior to the
intervention, she was able to elicit meaningful learning in her students. The engineering
design treatment and the targeted demonstrations may have even helped her teach in a
more dialogic and less authoritative way (Chin, 2006). While 75% of the classroom
teacher-student dialogue was authoritative in the Control class, 53% was authoritative in
the ETK class and only 44% was authoritative in the ETK+D class. The more open-ended
the activities and demonstrations, the less authoritative the teacher behaved when talking with her students as a class. This may have encouraged more students to engage in thinking about the activities instead of merely preparing to be tested on the material. Along these lines, it is interesting to consider that all three classes received statistically equivalent scores on the teacher-created end-of-unit test. Test items were traditional definition-based questions, and regardless of which class students were in, they regurgitated these definitions equally well. However, students in the ETK+D class who engaged in more open-ended dialog and thinking activities, performed better than the other two classes on the researcher-created HTE which required more deep conceptual knowledge, application and analysis of knowledge.

The implication that middle school teachers can successfully teach with open-ended engineering design-based curriculum is significant as more and more states adopt STEM initiatives and science teachers are called upon to implement engineering design-based curricula (Zinth, 2007). It is not an insurmountable challenge. Even a teacher who had never met an engineer taught her students the fundamentals of engineering to the degree where their attitudes toward it significantly changed in the positive direction after an intervention that lasted only 2 weeks.

The Gender Effect with Engineering Attitudes

The results of this study imply that engineering design activities embedded in middle school science classes can promote positive attitudes toward engineering and a better understanding of what engineering is as a career. Few students had scientific conceptions of engineering prior to the intervention, and attitudes toward engineering
were neutral as indicated by entrance interviews and scores on the ATES. Attitudes
toward engineering increased as a whole in both classes that received the treatment, yet
remained unchanged in the control class.

When gender was used as an independent variable in separately run t-tests for
each class, it became apparent that female students were to account for the positive
overall changes. For the males in each class, significance was not met. However, for the
females in the ETK class and the ETK+D class, there was a statistically significant
change from pre- to posttest. Given that the design challenge was set in a socially
relevant context that related engineering design to helping the environment and helping
animals, female students may have been more sensitive to the altruistic value of the
engineering design. Weisgram and Bigler (2006) studied middle school students’ interest
in science and found that altruism was valued more by girls than boys. Girls have also
traditionally been more drawn to a environmental engineering-type task, as most females
who choose engineering study environmental engineering whereas most males choose
mechanical engineering (Engineering Workforce Commission, 2002). However fewer
women overall choose to study engineering to begin with, with only 20% of engineering
bachelor’s degrees being awarded to women in 2005 (National Science Board, 2005). Of
the 791 middle school girls participating in the Weisgram & Bigler study, only 9% who
registered for a summer science institute indicated an interest in engineering. With fewer
females entering engineering fields, there are fewer role models in industry and
academia. With fewer than 7% of engineering faculty nationwide being female (Chesler
& Chesler, 2002), female engineer role models are scarce in higher education. Female
role models have been correlated to increased participation in science-related fields (Smith & Erb, 1986), and the same holds true for any non-traditional field, engineering included (Nauta, Epperson, & Kahn, 1998).

The engineering role model in this study was the teacher herself- a young, attractive, well dressed female. Baylor, Rosenberg-Kima, and Plant (2006) demonstrated that the impact of a “cool”, young, female engineering role model resulted in positive attitude changes toward engineering in female students whereas a male engineering role model had a lesser impact on modifying negative stereotypes. Dee (2006) reported that a female science teacher raised the achievement of girls by 4 percent of a standard deviation and lowered the achievement of boys by 4 percent of a standard deviation. The current study is unique in that gender was treated as an independent variable, and differences between genders were noted in terms of attitude change toward engineering. It is difficult to ascribe increased engineering attitudes in the female students in this study to one cause. It could be the altruistic nature of the context in which the design activity was set, or it could be the presence of a female role model. Only future research can address this question and tease apart the degree to which each component may have played. However, this study fills a hole in the research in that no other studies reviewed in the literature analyzed male and female attitudes toward engineering independently.

Limitations

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. 

*Design or Demos?*

> 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, and if four equivalent classes are not possible, perhaps
instead of an ETK class, a Control+D class will take its place. This would effectively compare engineering design with the targeted demonstrations to a Control class with targeted demonstrations.

**Teacher Preparation**

The teacher in this study successfully carried out teaching with an engineering-design-related curriculum even though her professional development for the task amounted to less than 8 hours. Because the teacher did not have any background in engineering, she learned what she needed to know from the curriculum and from discussions with the researcher. Observations of every class established treatment fidelity and helped the researcher conclude that the curriculum implementation was a success.

While it was impressive that a middle school teacher with no experience in engineering could successfully carry out an engineering design activity with her students, engineering as a career- and engineering design as a method- was not stressed to the degree it could have been. With additional professional development, it would be interesting to repeat this study with the same teacher to see whether a better conception of engineering as a career and avocation would elicit more positive gains in attitudes toward and understandings about engineering. Regardless of whether the same teacher is used in future research or not, modifications will be made to make sure that teacher participants have sufficient background knowledge not only about engineering, but about how to convey facets about engineering throughout the intervention. The teacher could be trained to refer to the students as engineers, refer to their design-build-test activities as engineering activities, and provide students with more opportunities to reflect on their
roles as engineers.

In addition to a possible lack of emphasis on engineering throughout the intervention, teachers make mistakes, and this particular teacher made no exception to that rule. There were many occasions in each class where she failed to convey the correct message. Sometimes students caught on and corrected her, or asked her to explain— but other times, her mistakes went unnoticed. She sometimes, but not always, failed to adequately differentiate between thermal energy and heat in her discourse. This may have been due to the fact that this was only her second year teaching physical science, and did not have a mastery of the concepts. Perhaps her undergraduate science preparation was weak in the physical sciences. However, she assigned readings in the textbook to all classes, and the reading passages gave sufficient definitions of all the science concepts. Mistakes of omission or commission were made with equal frequency in all classes. As far as mistakes of omission, students were not always given sufficient time to discuss the demonstrations that were used in all three classes. Whether the demonstrations were the targeted ones or the typical ones, the majority of the learning that came from them was due to students’ own thinking processes. Since the targeted demonstrations involved discrepant events, students may have put more thought into analyzing the outcomes, and even if the teacher had weak depth of knowledge, cognitive dissonance provoked students to put more thought into constructing knowledge. An example of a mistake of commission occurred when the teacher stated at one point with all three classes that an ocean has more heat than a cup of hot coffee, but failed to be more specific and state that the ocean has more thermal energy. The teacher herself may have had some
misconceptions about the difference between thermal energy and heat, but this was not determined during the entrance interview, as it was not anticipated.

There were no glaring differences between classes in terms of teacher mishaps, and this served as a control in providing equivalent learning opportunities. Future research will anticipate the issue of teacher misconceptions and include more rigorous preparation in both science content and engineering as an activity.

*Student Homogeneity*

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.

*Potential Researcher Bias*

The researcher, a former engineer, taught science through engineering design for
many years before she even knew research existed on the topic. She may have had a bias toward the approach, and this may have colored her collection of data and interpretation of the results—however objective and neutral she may have tried to be. To mitigate for this potential bias, a mixed methods study was used for methodological triangulation of various data sources. Quantitative instruments measuring attitude changes and content knowledge were compared to interviews with nearly half of the students in the study. This in turn was compared with classroom observations and analysis of student discourse during group efforts. All classroom observations and student discourse was transcribed for analysis, and the qualitative software, NVivo was used for coding the transcriptions. These efforts were all used to mitigate researcher bias, enhance the confidence of the results, and introduce as much objectivity as possible into a mixed-methods study.

**Suggestions for Future Research**

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.

The students in this study were from a rural school in a wealthy county. They
were primarily Caucasian and taking advanced-level coursework in math and science. It
would be beneficial to replicate this study with students of different socioeconomic and
academic backgrounds to see whether conceptions-based engineering design has the
potential to be more helpful, less helpful, or just as helpful with those populations in
allowing students to form better attitudes toward engineering and deeper concepts about
science.

Middle and high school-aged students are commonly targeted for engineering
design interventions (Jeffers & 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.

Additionally, the interesting gender-specific results about engineering attitudes
compel one to question whether some engineering design-based activities might attract
female students more than male students. An interesting continuation of this research
agenda would be to measure the attitude changes in both genders for different engineering design activities. Results of this work could potentially inform educators who wish to include some design activities that tend to interest male students more, and other design activities that tend to interest female students more. However, with the current deficiency of females choosing to enter STEM-related careers, determining which engineering design-related activities increase females' attitudes toward engineering would be beneficial to the diversity of potential scientists, mathematicians, engineers, and technologists. Currently, only 25% of the STEM workforce is female (Froschauer, 2006).

When conceptual learning was compared to design success for each group in the design classes, there was a negative correlation in the ETK class and a positive correlation in the ETK+D class. Conceptual learning was defined as HTE posttest scores and as pre-posttest changes. Design success was defined as the mass of the remaining penguin after testing the dwelling in the thermal oven. Small sample sizes inhibited the statistical corroboration of this finding. Future research should consider this tentative observation and investigate 1) whether students in the ETK class who spent more time thinking about how to achieve the design goal, spent less time thinking about the science and 2) whether the targeted demonstrations were mutually supportive to the effect that students in the ETK+D class tended to be more successful with the design goal when they were more successful learning the science.

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 so eloquently put it:

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).

Design comes naturally to children, as naturally as play. Spend time watching children in
a Kindergarten class, and watch them design and build and construct. What better conduit
through which to learn science?
REFERENCES


Erickson, F. (1986). Qualitative methods in research on teaching. In M. Wittrock (Ed.), *Handbook of research on teaching, (3rd Ed.*) (pp. 119-161). New York: Macmillan.


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Appendix A

Virginia Middle School Engineering Education Initiative

SAVE THE PENGUINS

ENGINEERING TEACHING KIT

An Introduction to Thermodynamics and Heat Transfer

University of Virginia
Charlottesville, Virginia

Written by Christine Schnittka

With thanks to Professor Larry Richards and his engineering students:
Kyle Adams, Chase Bennett, Rachel Cohn, Matt Gabriel, Will Gilliam, Chilton Griffin,
and Spencer Ingram
Students’ alternative conceptions of heat and temperature begin at a young age and persist through school. Because of the young age at which children experience warmth, experience being cold, and experience touching hot or cold things, naïve conceptions of heat, temperature and heat transfer are often resistant to change. Even young children intuitively develop a “framework theory of physics” to describe and explain the world they experience. The once-popular caloric theory that heat is a substance made of particles that flow still dominates children’s thinking, and they rely on their senses to measure temperature, not understanding the kinetic theory and its implications in heat transfer. The belief that cold is a substance that moves is prevalent with middle and high school students. These students also think that metal objects are naturally colder than plastic ones because metal “attracts” the cold. The directionality of heat transfer is not understood because heat is not seen to be a form of energy. Without explicit interventions designed to target these alternative conceptions, chances are that they will persist into adulthood. This Engineering Teaching Kit is designed to help students with science concepts related to heat and energy as well as teach them the basics of engineering design. They also come away with a sense of how engineers are people who design solutions to problems.

In the case of the *Save the Penguins* ETK, the broad context is global warming. Students learn that the energy we use to heat and cool our houses comes from power plants, most of which use fossil fuels to convert chemical energy to electrical energy. The burning of fossil fuels has been linked to increased levels of carbon dioxide in the atmosphere, which in turn has been linked to increases in global temperature. This change in temperature has widespread effects upon life on Earth. Penguins live in the southern hemisphere, primarily on the icy continent of Antarctica. As the Earth warms and ice melts, penguins lose habitat. Therefore, students see that better-designed houses that use less energy for heating and cooling have an effect on penguins. Energy efficient houses that minimize unnecessary heat transfer will draw less electricity from the fossil fuel burning power plants and not contribute as much to global warming.

Design-based science learning reflects the social constructivist theory of learning by having students work collaboratively in groups to solve problems and construct solutions, but learn certain skills through the modeling of their teacher. When students are involved in engineering design-based activities, they are not being told what to do- they are creating and innovating, making decisions with their peers based on their underlying knowledge. The role of the teacher is to guide students through their decision-making
processes and model new skills to be learned.

Through engineering design activities, students should be able to create their own knowledge of scientific principles through active manipulation and testing of materials and ideas. But because students come to school with their own understandings about the world and how it works, their understandings may not resemble those of scientists. The teacher must provide the opportunities for students to challenge and internally modify their prior beliefs. Therefore, social constructivists see that the role of the teacher is to help learners construct their knowledge through scaffolding and coaching. Social constructivists see that learners construct meaning through active engagement, not passive listening. Learners use and apply their knowledge to carry out investigations and create artifacts that represent their understanding. Learners work within a social context as they use language to express and debate their ideas. Learners engage in authentic tasks that are relevant to the student and connected with their lives outside of the school setting.

In design-based science activities, the teacher does not tell the students what to build. Instead, the teacher steps back and allows the students to take the primary lead in their own learning. Problem solving through authentic tasks that relate to students’ lives should serve to increase student interest and deeper conceptual knowledge.

Supplies:

This materials listed in Table 1 will supply one teacher with two classes of students—approximately 42 students. Some materials will be left over for future classes. Most materials can be purchased from a grocery store, hardware store, craft store, or large shopping mart. The Mylar space blanket, Monopoly money, and penguin-shaped ice cube trays may have to be mail ordered or printed. Suggested sites are provided below.
<table>
<thead>
<tr>
<th>Quantity</th>
<th>Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Bake Fresh paper baking cups, 50 count</td>
</tr>
<tr>
<td>1</td>
<td>Bake Fresh foil baking cups, 32 count</td>
</tr>
<tr>
<td>1</td>
<td>100% cotton balls, 200 count</td>
</tr>
<tr>
<td>2</td>
<td>Forster mini craft sticks, 150 count</td>
</tr>
<tr>
<td>1</td>
<td>Art Street construction paper pad, 42 count, 9&quot;x12&quot;</td>
</tr>
<tr>
<td>1</td>
<td>Creative Hands foam sheets, 12 count, 30cm x 45 cm</td>
</tr>
<tr>
<td>0.5 yd.</td>
<td>White felt fabric, polyester, 54&quot; wide</td>
</tr>
<tr>
<td>0.5 yd.</td>
<td>Pink felt fabric, polyester, 54&quot; wide</td>
</tr>
<tr>
<td>0.5 yd.</td>
<td>Blue felt fabric, polyester, 54&quot; wide</td>
</tr>
<tr>
<td>0.5 yd.</td>
<td>Green felt fabric, polyester, 54&quot; wide</td>
</tr>
<tr>
<td>1</td>
<td>Duck bubble wrap, 12&quot; x 30 feet</td>
</tr>
<tr>
<td>1</td>
<td>Heavy duty aluminum foil, 37.5 sq. feet</td>
</tr>
<tr>
<td>2</td>
<td>BP Medical Supplies Mylar foil rescue blanket, 62&quot; x 82&quot;</td>
</tr>
<tr>
<td>1</td>
<td>Hefty One Zip gallon storage bags, 17 count</td>
</tr>
<tr>
<td>6</td>
<td>Transparent tape, 1350&quot; long, .5&quot; wide</td>
</tr>
<tr>
<td>7</td>
<td>Aileen's Original Tacky Glue, 4 fl. Oz</td>
</tr>
<tr>
<td>14</td>
<td>Plastic shoebox, 6 qt. size</td>
</tr>
<tr>
<td>1</td>
<td>Tote bin, 12 gallon capacity</td>
</tr>
<tr>
<td>14</td>
<td>Dixie cups, clear plastic</td>
</tr>
<tr>
<td>1</td>
<td>Parker Brothers Monopoly money</td>
</tr>
<tr>
<td>2</td>
<td>Silicone penguin ice cube trays</td>
</tr>
<tr>
<td>12</td>
<td>Taylor digital instant read pocket thermometer</td>
</tr>
<tr>
<td>3</td>
<td>Clamp light, 8.5 inches</td>
</tr>
<tr>
<td>3</td>
<td>Light bulb, 150W clear</td>
</tr>
<tr>
<td>20</td>
<td>Paper cups</td>
</tr>
<tr>
<td>1</td>
<td>Six pack of soda</td>
</tr>
<tr>
<td>1 each</td>
<td>Wool sock, cotton sock, paper toweling, plastic wrap</td>
</tr>
<tr>
<td>1 each</td>
<td>Wood tray, silver tray</td>
</tr>
<tr>
<td>2</td>
<td>Top Fin flexible aquarium thermometers, large</td>
</tr>
<tr>
<td>1</td>
<td>Large easel pad (Post-It brand or store brand) with at least 20 sheets</td>
</tr>
<tr>
<td>8 of each</td>
<td>Silver spoons and Plastic spoons</td>
</tr>
<tr>
<td>1</td>
<td>Homemade cardboard house with black painted roof</td>
</tr>
</tbody>
</table>

BP Medical Supplies: http://www.bpmedicalsupplies.com/main.sc

Silicone Penguin Ice Cube Trays at Kitchen Crafts:

Thermometers: www.petsmart.com

Preparations of Materials: Prepare the felt, foil, construction paper, foam, Mylar, and bubble wrap by cutting the materials into uniform squares. If you have a quilting ruler and cutting board, 3" x 3" pieces are convenient. If you want each piece to be sized metrically, you can cut the pieces into 10cm x 10cm squares. Store each material in separate 1 gallon storage bags for easy retrieval. See Figures 1 and 2 for suggested storage configuration.

Figure 1. Materials cut and packaged.
Day 1 – Introduction to the Unit/ Lesson on Insulation

Objectives: The first objective is to introduce students to the environmental conditions affecting penguins, the way global warming is tied to energy consumption, and the role engineering can play in helping both the environment and penguins. The second objective is for students to witness and discuss a series of discrepant event demonstrations related to heat transfer, forming an understanding of insulation, heat, and temperature. The third objective is for students to begin a storyboard-type poster for the unit.

- Students will be able to describe engineers’ role in society.
- Students will be able to explain how global warming is related to loss of ice at the Earth’s poles.
- Students will be able to explain how humans contribute to global warming.
- Students will be able to brainstorm ways engineers might be able to help slow the process of global warming through the design of more energy efficient buildings.
- Students will be able to define heat as the transfer of thermal energy.
- Students will be able to define temperature as a measure of the average thermal energy in a particular place.
• Students will be able to define conduction as the transfer of thermal energy through a solid material.

• Students will be able to explain the difference between heat and temperature.

• Students will be able to demonstrate that some materials are better insulators than others, i.e. felt insulates better than foil.

• Students will be able to apply knowledge that some materials are better than others at reducing the transfer of thermal energy.

• Students will be able to compare different materials to determine which ones are better at preventing heat transfer.

1. Pre-assessment on heat transfer (10 minutes)
2. Introductory PowerPoint lecture on engineering, penguins, and heat transfer. (30 minutes)
3. Introduction to the storyboard poster. (15 minutes)
4. Demonstration 1 – Soda cans wrapped in different materials (20 minutes)

Day 2 – Conduction, Radiation, and Convection

Objectives: Today’s objectives are to get students thinking about heat transfer through conduction, radiation, and convection, help them visualize how heat transfers from warmer to cooler objects, how certain materials are better heat conductors than others, and how certain materials reflect or absorb radiation, and how convection currents are due to differences in density.

• Students will be able to define conduction as the transfer of thermal energy through a solid material.

• Students will be able to explain why thermal energy moves from areas of higher temperature to areas of lower temperature.

• Students will be able to apply knowledge that some materials are better than others at reducing the transfer of heat.

• Students will be able to demonstrate that some materials are better conductors than others, i.e. metals conduct heat better than wood.

• Students will be able to explain how thermal energy transfers through solid materials as vibrating atoms collide with each other.

• Students will be able to compare different materials to determine which ones are better at preventing heat transfer.
• Students will be able to define radiation as the transfer of thermal energy through space.

• Students will be able to explain that when dark objects absorb radiation, this energy is transferred into thermal energy.

• Students will be able to demonstrate that materials that are light colored or shiny reflect radiation.

• Students will be able to demonstrate that some materials are better at reflecting radiation than others.

• Students will be able to define convection as the transportation of thermal energy through the movement of a fluid from one place to another.

• Students will be able to describe that fluids expand when heated which makes them less dense, that less dense fluids have more buoyancy, so they tend to float above fluids with more density, and that when fluids cool, they contract which makes them denser.

1. Review insulation demonstration from day before (10 minutes)
2. Demonstration 2 – Feeling the temperature of wood and silver trays (10 minutes)
3. Demonstration 3 – Melting penguins in plastic and silver spoons (15 minutes)
4. Demonstration 4 – Convection in a black-roofed house (20 minutes)
5. Demonstration 5 – Space blanket demonstration of radiation reflection (5 minutes)
6. Documenting learning on story board (10 minutes)

Day 3 – Review of Heat Transfer/ Introduction to Experimental Design

Objectives: Today’s objectives are to review the three methods of heat transfer, introduce students to their kit of materials, model how to conduct experiments with the materials, and have students conduct experiments with the materials.

• Students will be able to compare different materials to determine which ones are better at preventing heat transfer.

• Students will be able to discern which type of heat transfer a material prevents.

1. Review exit card on methods of heat transfer (15 minutes)
2. Introduce students to kit of materials (5 minutes)
3. Model how to conduct experiments at experimentation stations (15 minutes)
4. Students test materials and keep records of their work on storyboard (30 minutes)
5. Teacher and students discuss all the experiments done in class this day (10 minutes)
Day 4 – Students Design and Construct Dwellings

Objectives: Today’s objectives are to design and construct prototype dwellings for penguin-shaped ice cubes based on the knowledge gained from experiments conducted on the materials.

- Students will be able to combine information about different materials to synthesize a unique design.
- Students will be able to create a device which reduces heat transfer and keeps an ice cube from melting.

1. Students conduct additional experiments as needed and share results (10 minutes)
2. Students design initial dwelling (15 minutes)
3. Students purchase additional materials necessary (10 minutes)
4. Students construct dwelling (40 minutes)

Day 5 – Testing the Dwellings

Objectives: Today’s first objective is to have students test their dwellings in a hot box with radiant, conductive, and convective heat. The second objective is for students to analyze the dwellings and determine which features were most successful and reducing heat transfer, and identify the type of heat transfer reduced.

- Students will be able to evaluate devices designed to reduce heat transfer, compare them, and conclude how they work.
- Students will be able to judge the effectiveness of devices designed to reduce heat transfer.

1. Put designs in hot box for 30 minutes (30 minutes)
2. Have students research innovations in building materials on computers while penguins melt. Or use PowerPoint presentation, Innovative Building Materials.
3. Analyze and discuss results (20 minutes)
4. Have students record modifications they would like to do on their design (20 minutes)

Day 6 – Revision and Final Testing

Objective: To make improvements and repeat the testing process.

1. Revisions (20 minutes)
2. Final testing (30 minutes)
3. Post assessment and poster finalization while final testing takes place
4. Wrap-up discussion (20 minutes)

Supplemental Information

Students will be working in groups. Ideally, groups of three work well. Either allow students to pick their own groups, or assign them based on what you know about how your students get along and work together. Since students will be working with the same group members for the duration of this ETK, it is best if the students like one another and work well together. Have students sit together with their group members from the beginning of this unit.

UNIT DETAILS

Day 1 – Introduction to the Unit/ Lesson on Insulation

Preparation:

- Photocopy the Heat Transfer Evaluation for students.
- Photocopy the Engineers handout for students.
- Study and practice the PowerPoint presentation on the unit. Print off notes for yourself if you need them.
- Set up an LCD projector and screen with speakers attached to your computer.
- The night before, place six cans of soda in your refrigerator at home.
- The next morning, before you come to school, wrap each one up in the following materials: wool sock, cotton sock, aluminum foil, paper toweling (you may have to tape this), plastic wrap, and nothing. Place each one in a paper lunch bag and label it on the outside with a thick marker. Bring to school.
- Make sure Excel is installed on the computer that will be projecting. Prepare a template for recording temperatures or use the one provided. See Table 2 for sample template
- Purchase large poster sheets that have a sticky strip on top (like large Post-It easel notes). Make sure you have one for each group, plus a few extras.

Step 1: Assess student’s prior knowledge about heat transfer with the Heat Transfer Evaluation. Collect the assessments, score them, but do not return or discuss them with students. This instrument is based on misconceptions research and has been assessed for
face and content validity, construct validity, and reliability. The assessment will provide you with information about your students' misconceptions about heat.

Step 2: Deliver PowerPoint presentation on engineering, penguins, and heat transfer. Beforehand, read through all the notes provided for each slide, and research each highlighted engineer for more information through the links provided. The goal is to get the students to be able to make the connections between the plight of penguins, global warming, energy consumption, materials that regulate heat transfer in our homes, and the role of engineering in society. Be sure to involve students in a continuous discussion through the discussion prompts provided. Provide the Engineers handout in case students wish to follow along or do additional research with the Internet links provided.

Step 3: Introduce the concept of the story board. A story board is like a comic strip in that it tells a story through drawings and words divided up into sections that flow on into another. Each time students learn a new concept, do an experiment, create a design, or test a design, it should be recorded on the story board for teachers and students to see and comment on. Ideally, the storyboard is on the wall for easy viewing. See Figure 3 for a sample story board. You might want to show students a sample storyboard.

Figure 3. Sample Story Board

For more information about this instrument, contact Christine Schnittka at cgs2d@virginia.edu.
Step 4: Tell a story that goes something like this: You want to bring a cold soda on a field trip and drink it for lunch, but you want it to still be cold when you drink it and you don’t know what the best thing would be to keep it cold. Ask students for suggestions and reasons why they think their method would work. If a student suggests that their method will—

**keep the cold in**—remind them that only heat transfers. That’s why it’s called heat transfer. If only heat can transfer, what is their method really doing? (Keeping the heat out!)

Tell students that you designed an experiment with some things you found around your house that you thought might be good at keeping the heat out. Bring out the six lunch bags and show students what is inside. See Figure 4. Have them make predictions on a piece of paper or in their science journals as to which one will be the coldest at this point. Have them rank the materials. Most students will rank the aluminum foil as being the best material to keep the soda cold, and the wool sock (or the control) as the worst. Ask students to justify their reasoning. If a student suggests that the wool sock will—

**warm up the soda because socks warm your feet**—remind them that socks do not generate heat, they trap the thermal energy of the feet. Ask, “Would the socks trap the heat outside of the soda can??

Justify your choice of paper toweling as a possible material to block heat transfer. Tell students that you know that builders blow paper pulp into attics to keep heat from transferring into our out of a house. Also, tell them that some homeless people use newspapers to line their clothes in the wintertime to help prevent the thermal energy from their bodies from escaping. If students say that

**their parents wrap their sodas in aluminum foil**—remind them that traditions get passed down for generations without question. Today we will question the tradition.
Figure 4. The Cans Demo

After students have made their predictions and you have discussed their reasoning as a class, pop the tops and have student volunteers insert digital thermometers and record the temperatures in the spreadsheet. Do not unwrap the cans, as they will need to stay insulated if you have additional classes this day, or if you want to track the temperature changes over time. Remind students of the value of having a control when experimenting with materials. Ask if they can tell you why having a control is important. Enter the temperatures in an Excel spreadsheet projected in the classroom, and use the graph utility to create a bar graph. Table 1 is a sample Excel spreadsheet while Figure 5 is a sample bar graph. Figure 6 depicts how the temperature may change over the course of a class period.

Table 2

*Sample Template for Recording Temperatures*

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature at Time 1, °F</th>
<th>Temperature at Time 2, °F</th>
<th>Temperature at Time 3, °F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wool sock</td>
<td>60.4</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>Paper towel</td>
<td>60.4</td>
<td>63.7</td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>61.3</td>
<td>64.6</td>
<td></td>
</tr>
<tr>
<td>Plastic wrap</td>
<td>62.1</td>
<td>65.1</td>
<td></td>
</tr>
<tr>
<td>Cotton sock</td>
<td>63.5</td>
<td>66.4</td>
<td></td>
</tr>
<tr>
<td>Nothing</td>
<td>64.2</td>
<td>67.1</td>
<td></td>
</tr>
</tbody>
</table>
Your students may be very surprised that the wool sock (make sure it is wooly and thick) and the paper towel do a very good job at preventing heat transfer. Describe wool and plush paper toweling as good insulators because they trap air and prevent the air from moving around. Describe paper as being made of dried up hollow cells from plant matter. Tell students that trapped air is an excellent insulator and ask if they have ever seen the pink or yellow fiberglass insulation used in houses? Ask students to make an inference as to why the aluminum foil and plastic wrap do not turn out to be good insulators. They may infer that the foil and plastic do not trap air.

The results from this experiment should be illustrated in the first cell of the story board.

Figure 5. Temperatures after three hours outside refrigerator in paper bag.

After an hour, a second measurement helps discriminate the small differences between some materials. If you don’t have time to repeat the measurements with your class, perhaps do it yourself and report the values the next day for further discussion. Ask students:

- Why do they think the wool sock prevented heat transfer better than the paper towel?
• Why do they think the aluminum foil performed better than the plastic wrap?
• What is it about a cotton sock that makes it a poor insulator?
• Why is it better to wear wool in the winter than cotton?

This is a good time to discuss the difference between heat and temperature. Some students may think that temperature gets transferred since temperature changes. Many use the words interchangeably and do not understand their true meaning. Use these definitions and descriptions to help students understand what heat and temperature are, and how they are different from each other:

**Heat:** Heat is the transfer of thermal energy. Thermal energy exists when molecules are in motion; when the atoms or molecules in a substance vibrate. They have kinetic energy, which creates thermal energy. The amount of thermal energy something has is the sum of the kinetic energy of all the particles. That’s why a bathtub of water has more thermal energy than a sink of water when the water is the same temperature in both. As something loses thermal energy, these vibrations slow down. As something gains thermal energy, these vibrations increase. If enough thermal energy is added to a substance, the vibrations may even cause a solid material to lose its form and melt, or a liquid substance to evaporate, or a gaseous substance to expand as the distance between particles increases. Thermal energy can be transferred from one place to another when there is a temperature difference. Heat transfer always occurs from the place where there is a higher temperature to the place where it is cooler. Heat transfer in a bathtub occurs from the hot water to the cooler air and the cooler floor and the cooler tub sides, and the cooler person in the water.

**Temperature:** Temperature is a measure of the average kinetic energy that the particles in a substance have at a particular location. There are many scales used to measure temperature. In the Kelvin scale, 0 degrees Kelvin represents the absence of all kinetic energy, the absence of all molecular or atomic vibrations. A cup of boiling water may have a higher temperature than a bathtub of warm water because the average kinetic energy of the particles is higher. However, if you were to sum up the kinetic energy of all the water molecules in the tub, it would no doubt have a higher total thermal energy. Temperature is like counting the money one person in a room has in his or her pocket. Thermal energy is like counting the money that everyone in the room has and adding it all up. Heat transfer occurs when thermal energy transfers.

Have students define heat and temperature in their own words in the second cell of their
Day 2 – Conduction, Radiation, and Convection

Preparation:

• Find a wooden tray (cutting board or pizza board) and a silver tray. Tape an aquarium thermometer strip to the underside of each board. They will each display room temperature. Top Fin makes them in a large, easy to read size.
• Make penguin-shaped ice cubes the night before so they can be used in a demonstration on this day.
• Borrow or bring to school some silver spoons and plastic spoons, one of each for each group. If silver cannot be procured, stainless steel will do, but silver is a better conductor of heat, and the demo will work better.
• Construct a cardboard house with a roof. Paint the roof black. Cut a flap in the bottom so you can cool the house off quickly. Insert a thermometer in the attic space and another near the floor of the house. See Figure 10 for a sample house. This house will be used for two demonstrations. Cut a piece of Mylar space blanket so that it drapes over the roof and covers all the black paint.

Step 1: Review the heat insulation demonstration from the class before. Were all the materials used “heat insulators”? Certainly the application of all the materials prevented some heat transfer since the soda can with no materials wrapped around it gained the most heat energy. Some students will be confused about the term, “insulation” because it
applies to electricity as well as heat transfer, and because it is a term used very loosely in everyday language. Give students the scientifically accepted version of the definition of the term, and ask them if all the materials were insulators? If aluminum is not a thermal insulator, how did it prevent heat transfer? The answer probably lies in the air trapped between the aluminum can and the aluminum foil. See if you can get students to reach this understanding. Materials which are not heat insulators may be heat conductors. Metals are good heat conductors. When the aluminum foil touches the soda can, it actually conducts some heat from the surroundings into the can.

**Heat Insulator:** A material which reduces the rate of heat transfer.

Step 2: Demonstrate how different a silver tray and a wooden tray feel when they are touched. See Figure 7. Both trays are at room temperature, but students will swear that the silver tray is colder. Pass both trays around the room and ask students to touch them and tell you which one is colder. Accept any answers. The next demonstration will tie into this one.

Step 3: Pass out a silver spoon and a plastic spoon to each group of students. Ask them which spoon feels colder. They can place the spoons on their cheeks because the face is more sensitive than the hands. Students will likely respond that the silver spoon feels colder. Now, ask students to predict which spoon will work best and keeping an ice cube cold. Many will predict the silver one since it feels colder. Pass out two penguin-shaped ice cubes for each group and have students take turns holding the spoons in their hands. See Figure 8. After three minutes (one minute for each group member) ask students to explain why the penguin in the plastic spoon is not melting while the penguin in the silver spoon is quickly turning to water. This is a good opportunity to introduce the definition of the term, conduction.

**Conduction:** Conduction is the way thermal energy transfers from one substance to another by direct contact. It can be the direct contact between solids, or between a solid and a fluid. Kinetic energy is transferred as higher temperature vibrating molecules or atoms collide with cooler matter, increasing the kinetic energy of the cooler substance.
Remind students that heat transfers from where the temperature is higher to where the temperature is lower. Ask them:

- What causes the ice to melt?
- Which spoon made the ice melt faster?
- Why?
- Which spoon is a conductor?
- Which spoon is an insulator?
- Would a penguin shaped ice cube last longer sitting on a metal surface or a plastic surface?
Have them complete a section of their story board with the definition of conduction and a drawing of the spoons with arrows showing the direction heat transfers. See Figure 9 for a student example.

Help students come to the understanding that the metal spoon feels colder because heat is leaving the hand. Remind them that “cold” does not travel or transfer, only heat does. Ask, “When you touch the metal spoon to your cheek, why does it feel cold?” Make sure that all students understand the concept of conduction, the concept of kinetic molecular energy, and the direction heat transfers before proceeding to the next step.

Figure 9. Student drawing of penguins in spoons

Step 4: Retrieve the wooden and silver trays. Ask students again which one felt colder. Ask:

- Do you think the silver tray was actually colder?
- Why did it feel colder?
- If it wasn’t actually colder, what temperature do you think it was?
- How could we find out the temperature of each tray?

Then show students that you have thermometer strips taped to the back of each tray. Have students look at the strips and verify that the trays are the same temperature.
You might want to ask students if they have ever experienced this phenomenon, where metals feel colder than nonmetals when they are actually the same temperature. Some students might bring up the “don’t touch your tongue to a metal post in the wintertime” story, and you can have the class try and explain the heat transfer process going on when that happens.

Step 5: Show students the cardboard house you built (See Figure 10). Show them the thermometers and have someone record the temperatures in the attic and lower floor. Turn a shop light on over the cardboard house. The bulb should be 150 Watts. Position the light approximately 10-12 inches above the roof of the house. Have student volunteers call out the temperatures while another student records them. Within a few minutes, the temperature in the attic space will approach 100°F (38°C) while the temperature in the lower floor will only be around 72°F (22 °C). See the document, Hot House, for some typical temperatures.

Tell students that thermal energy transfers in other ways too; conduction is not the only way heat transfers. See if some students know the other methods of heat transfer and if they can identify why the attic of the house is getting so hot. The attic is getting hot because the black roof is absorbing infrared and visible light radiation from the light. This radiation is converted into heat on the roof. The air in the attic is getting hot because of conduction. The hot roof transfers its energy to the air next to it inside. Some students may say:

heat rises — and if a student makes this statement, remind them that heat is not a substance. Tell them that hot air can rise, but that heat is the transfer of thermal energy and energy can certainly transfer from one place to another, but thermal energy can transfer sideways, downwards, or upwards. However, hot air can rise. In this case, hot air rising is not causing the hot attic. Energy is being transferred from the light source to the black roof, and thermal energy is conducting through the roof into the air of the attic. The hot air does not fall and heat the lower part of the house because hot air is less dense than cooler air.
Now, have your student volunteers sit down because this next part is the most important one. Tell students that you are going to turn the house upside down and ask for predictions about the temperature of the attic and the first floor. When you turn the house over, call out the falling temperature of the attic space and the rising temperature of the first floor space. They will eventually reach equilibrium. Ask students to explain what they think is going on. Encourage your students until they can articulate that the hot air in the attic is now rising, and the cooler air in the first floor is now sinking. Tell them that this is called convection.

**Convection:** Convection occurs when moving fluids (gases or liquids) rise and fall due to differences in density caused by differences in thermal energy.

Have students complete a section of their story board with the definition of convection and a drawing of the house with arrows showing the direction heat transferred when the house got flipped upside down.
Step 6: After the house is cooled down to room temperature, place it under the lamp again, but this time drape the roof with a piece of Mylar space blanket. Ask students for predictions. Once again, have students call out the temperatures and record them. You will find that the attic air does not get nearly as hot. It might not even reach 76°F (24 °C), and the first floor will remain quite cool. This is a good time to introduce the third method of heat transfer, radiation. Tell students that the black roof absorbed the radiation from the light source, but that the space blanket reflected the radiation away, keeping it out of the house.

Have a student volunteer place their hand under the hot lamp. Then block the light with the space blanket, and ask the student what they felt. Immediately, the heat transfer stops, and the hand feels cooler.

**Radiation**: Radiation is the transfer of energy in the form of electromagnetic waves. Visible light and infrared light are both forms of radiation that transfer heat.

- How does Earth get its heat? (It is transferred from the sun.)
- How does the heat from the sun get to Earth? (Through radiation)
- Does the Earth reflect radiation from the sun? (Yes! The clouds reflect it, snow reflects it, water reflects it.)

Have students complete a section of their story board with the definition of radiation and a drawing of the house with arrows showing how radiation was reflected off the Mylar space blanket.

Finish up this class with a review of the three methods of heat transfer. If there is time, pass out the exit card printed below and have students complete it in pencil. Otherwise, give it first thing the following class day. Allow students time to complete their story boards if needed.

**Day 3 – Review of Heat Transfer/ Introduction to Experimental Design**

**Preparation:**

- Prepare kit boxes for each of your student groups. Place a sample of each material in the box. If a material comes in several colors, just choose two colors. Students can trade or share while testing. Each sample should be cut approximately 3” x 3” square or 10cm x 10cm. Number each box so teams can remember which box is theirs. See Figure 11 for an example.
- Prepare the “cooker” that will be used to test the students’ designs. Take a storage bin and mask the sides so they stay neat and clean, then spray paint the bottom black. After it is dry, line the sides with heavy duty aluminum foil. You will be shining three shop lights into the cooker. See Figure 12 for an example of the cooker.
• Set up three or more experimentation stations around the classroom with shop lights clamped to a stand or cabinet handle so that they are approximately 18” off the countertop. Turn the lamps on so the countertop heats up. Place a digital timer and two digital thermometers at each station.
• Prepare baggies with $250 of Monopoly money in each. Put one baggie in each team box.

Step 1: Make sure students understand the three methods of heat transfer.

Step 2: Pass out the kits of materials to students and let them look at the materials. Tell them that they are going to design and build an igloo that will keep a penguin-shaped ice cube from melting. However first, they need to find out about the materials they have to work with. They have to test them to see which ones they want to use. Some will be better than others at preventing different kinds of heat transfer. When they build their igloo, they will be given a budget to work with, so they need to decide which materials are worth purchasing.

Figure 11. Box of sample materials

Show students the “cooker” that will test their designs. Have them identify all the forms of heat transfer that might take place and where the heat will be coming from. There will be conduction at the black-painted floor, radiation from the three shop lights and reflected off the foil sides, and convection currents as hot air rises off the black floor.
Step 3: Model how to conduct experiments at experimentation stations. To do this, talk out loud as you think about whether you want to use aluminum foil or Mylar space blanket to reflect radiation. Talk about how you will measure the temperature underneath each material as light is shining on it. Call the temperature your independent variable because “I” measure the “I”ndependent variable. Call your materials the dependent variable because the results depend on them. You might want to model some poor experimental techniques and ask students what is wrong with each.

- Put the samples on the counter and place a thermometer on top of each. (The sample will not be blocking radiation.)
- Use only one thermometer and take the temperatures at different times. (The temperature might be higher under one sample because more time has elapsed.)
- Test each material one at a time and do not time the trials. (You are not controlling for time.)
- Use a large piece of aluminum foil but a small piece of space blanket. (Not controlling for size.)

Remind students about controls that must be kept the same in order to do fair experiments. Remind them to record their independent and dependent variables. Have them construct one square on the story board for each experiment they do. Encourage groups to test different materials because all the results will be shared between groups.
Remind students that they can modify the materials. For example, they can compare two sheets of construction paper to only one sheet. Or they can compare two sheets separated by cotton batting to two sheets separated by bubble wrap. Or they can wrap the paper cup in different materials and test the temperature underneath the cup. If your counter is hot enough, they can test materials for their ability to insulate from conduction. Also remind students that the black bottom of the cooker will give off radiation because all hot objects radiate heat.

After each group has conducted at least one experiment, discuss the experiments with the class. Keep track of the results on the board, and have students complete a story board square with a list of which materials are better than others. Be sure to engage students in an analysis of why some materials might have performed better than others. Have students identify which type of heat transfer the material was reducing. For example, the white felt allows more light to travel through it than the white construction paper, so it allows more radiation to penetrate. Or, one sheet of Mylar is actually transparent to light while two sheets are not. Be sure to point out any experimental techniques that may not be correct. Remind students that they can continue to test materials and combinations of materials.

**Day 4 – Students Design and Construct Dwellings**

**Preparation:**

- Make sure you have glue and tape and scissors available.
- Keep the experimentation stations set up in class today for additional tests.
- Photocopy the Engineering Design Process handout
- Have some ice penguins available. Students may want to compare different ideas with them. Prepare the penguins by using an accurate medical syringe to fill each well with exactly 10ml of water for a 10 gram penguin.

Step 1: Allow students some more time to conduct experiments on materials or combinations of materials. Remind them that combinations can behave very differently from the single materials alone.

Step 2: Allow students to purchase additional materials from the Igloo Depot. A suggested price list is as follows in Table 3. These prices are marked up, based on the actual price of the materials.

Whether materials are purchased or were proved as free samples, students should keep track of the cost of materials that go into their igloo. If someone were to purchase supplies to re-create the design, what would it cost? Have students keep track of this on
Table 3

*Construction materials and suggested price*

<table>
<thead>
<tr>
<th>Item</th>
<th>Count</th>
<th>Price per item</th>
<th>1000x markup</th>
<th>Sale Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bake Fresh paper baking cups, 50 count</td>
<td>50</td>
<td>$0.0336</td>
<td>$33.60</td>
<td>$30.00</td>
</tr>
<tr>
<td>Bake Fresh foil baking cups, 32 count</td>
<td>32</td>
<td>$0.0334</td>
<td>$33.44</td>
<td>$30.00</td>
</tr>
<tr>
<td>100% cotton balls, 200 count</td>
<td>200</td>
<td>$0.0091</td>
<td>$9.10</td>
<td>$10.00</td>
</tr>
<tr>
<td>Forster mini craft sticks, 150 count</td>
<td>150</td>
<td>$0.0192</td>
<td>$19.20</td>
<td>$20.00</td>
</tr>
<tr>
<td>Construction paper pad, 42 count, 9&quot;x12&quot;</td>
<td>504</td>
<td>$0.0036</td>
<td>$3.61</td>
<td>$4.00</td>
</tr>
<tr>
<td>Foam sheets, 12 count, 30cm x 45 cm</td>
<td>72</td>
<td>$0.0414</td>
<td>$41.39</td>
<td>$40.00</td>
</tr>
<tr>
<td>White felt fabric, polyester, 54&quot; wide</td>
<td>48</td>
<td>$0.0415</td>
<td>$41.46</td>
<td>$40.00</td>
</tr>
<tr>
<td>Pink felt fabric, polyester, 54&quot; wide</td>
<td>48</td>
<td>$0.0415</td>
<td>$41.46</td>
<td>$40.00</td>
</tr>
<tr>
<td>Blue felt fabric, polyester, 54&quot; wide</td>
<td>48</td>
<td>$0.0415</td>
<td>$41.46</td>
<td>$40.00</td>
</tr>
<tr>
<td>Green felt fabric, polyester, 54&quot; wide</td>
<td>48</td>
<td>$0.0415</td>
<td>$41.46</td>
<td>$40.00</td>
</tr>
<tr>
<td>Duck bubble wrap, 12&quot; x 30 feet</td>
<td>200</td>
<td>$0.0099</td>
<td>$9.85</td>
<td>$10.00</td>
</tr>
<tr>
<td>Heavy duty aluminum foil, 37.5 sq. feet</td>
<td>250</td>
<td>$0.0039</td>
<td>$3.94</td>
<td>$4.00</td>
</tr>
<tr>
<td>Mylar foil rescue blanket, 62&quot; x 82&quot;</td>
<td>426</td>
<td>$0.0046</td>
<td>$4.60</td>
<td>$5.00</td>
</tr>
</tbody>
</table>

Step 3: Give students plenty of time for construction. It’s important that the teacher discuss design decisions with students. Go over the Engineering Design Process handout with them. Without giving away what WE know is best, it’s important to pull creative and logical thinking out of the students. You might want to ask:

- If you were a ray of light, could you get into the igloo somehow and melt the penguin?
- Can convection currents rise and fall inside your igloo?
- How is the heat from the black floor going to transfer into your igloo?
- What are some ways to stop radiation? convection? conduction?
- What are some design features of your own house that keep thermal energy out in the summer time?
- Why did you choose that color?
- Did you do a test on that material to make sure it works like you want it to?
- How does one layer of that material compare to two layers?
- If air is such a good insulator, how can you trap more air?

Make sure that students document their design on a story board square, labeling the materials the use and indicating which type of heat transfer is being prevented. See Figure 13 for sample.
Day 5 – Testing the Dwellings

Preparation:

- Have something for students to do while the designs are in the cooker. You can show them part of Inconvenient Truth, part of March of the Penguins, or even part of Happy Feet. Or you can have them research modern engineered building materials on computers. If computers are not available, you can deliver the PowerPoint presentation called Innovative Building Materials provided in this ETK.
- Find one plastic Dixie cup for each group that has the same mass. Most will be 2.2 grams. Distribute one to each group.
- Set up the lamps around the foil-lined cooker. See Image 11 for the configuration. When the temperature on the bottom of the cooker is over 40°C or 100 °F, it is ready to cook. Do not use digital thermometers to measure this, as the heat will destroy the LCD display.
- Prepare a chart on the board or on a piece of poster paper for students to fill in their results. See Figure 14 for suggestions.

Step 1: Have students hold their Dixie cups with the mass written on them in a permanent marker. Plop the ice penguins into the cups and instruct students to put the penguins in their igloos as quickly as possible. Set a timer and place the igloos in the cooker so that they are evenly spread apart from each other. Cook for 20 minutes. This is approximately the time it takes for a homeless ice penguin to totally melt away. You could cook for 30 minutes if time permits.

Step 2: Depending on your students, have them research innovations in building materials, listen to a presentation about building materials with images, or simply show students video clips from March of the Penguins, Happy Feet, or Inconvenient Truth. A PowerPoint presentation about building materials is included in this ETK.

Step 3: As soon as time is up, have students retrieve their igloos and take the remaining ice out, placing it in the Dixie cup. Have students find the mass of their penguin by subtracting the mass of the cup. Write all the results on the board along with the cost of each igloo dwelling.
Figure 13. Sample student design.

<table>
<thead>
<tr>
<th>Team Name</th>
<th>Car of Dwelling</th>
<th>Final Mass</th>
<th>Mass Lost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glitter Cthulhu Fags</td>
<td>$430</td>
<td>4.9 - 2 2 - 0 1 7</td>
<td>5.3 g</td>
</tr>
<tr>
<td>Wooly Alp asking</td>
<td>$64 5</td>
<td>8.1 - 2 2 - 6 0 7</td>
<td>4.1 g</td>
</tr>
<tr>
<td>Ice Penguin</td>
<td>$27 4</td>
<td>6.2 - 2 2 - 5 1 1</td>
<td>6.9 g</td>
</tr>
<tr>
<td>Susan Sea</td>
<td>$41 0</td>
<td>8 2 - 2 2 - 2 6 0</td>
<td>4.9 g</td>
</tr>
<tr>
<td>Cheesy Cheese Cubes</td>
<td>$88 0</td>
<td>3 3 - 2 2 - 7 1 4</td>
<td>5.5 g</td>
</tr>
<tr>
<td>Soccer Hotties</td>
<td>$4 8 5</td>
<td>5.0 - 2 2 - 1 9 6</td>
<td>4.6 g</td>
</tr>
<tr>
<td>Funky Butter</td>
<td>$4 9 0</td>
<td>3.3 - 2 2 - 5 1 1</td>
<td>3.9 g</td>
</tr>
<tr>
<td>John Bureas</td>
<td>$3 8 4 8 9 0</td>
<td>7 2 - 2 2 - 2 0 0</td>
<td>7.0 g</td>
</tr>
<tr>
<td>Melting Penguins</td>
<td>$3 8 6 8 4 0 0 0</td>
<td>4.2 - 2 2 - 2 0 0</td>
<td>4.5 g</td>
</tr>
<tr>
<td>THC</td>
<td>$5 8 6 6</td>
<td>4 2 - 2 2 - 2 2 2</td>
<td>4.5 g</td>
</tr>
<tr>
<td>Uh Oh Ores</td>
<td>$2 8 4 0 0 0</td>
<td>7 4 - 2 2 - 5 2 2</td>
<td>6.8 g</td>
</tr>
<tr>
<td>Eruv Fries</td>
<td>$3 4 0 6 5 0 0 0</td>
<td>6 5 - 2 2 - 9 2 0</td>
<td>5.7 g</td>
</tr>
<tr>
<td>Eruv Fries</td>
<td>$3 4 0 6 5 0 0 0</td>
<td>8 3 - 2 2 - 2 2 2</td>
<td>3.9 g</td>
</tr>
<tr>
<td>The PB Gunter</td>
<td>$6 4 0 0 5</td>
<td>5 8 - 2 2 - 7 1 0</td>
<td>6.3 g</td>
</tr>
<tr>
<td>Toces Dwerker Finked</td>
<td>$4 7 0</td>
<td>4 2 - 2 2 - 5 1 0</td>
<td>3.0 g</td>
</tr>
</tbody>
</table>

Figure 14. Possible chart of results
You might want you columns to be labeled differently. Make sure students record their results on a square on their story board.

Step 4: The most important part of the class period is the discussion. Gently and tactfully, have the class analyze the igloos that did the best job at preventing heat transfer. Also, have the class analyze the igloos that did not perform as well. From this discussion, students can learn what features were most effective at preventing heat transfer, and which kind. As you discuss the design features, be sure to point out which features prevented which type or types of heat transfer.

Step 5: Have students record the modifications they would like to do on their design tomorrow in class. Have them record these ideas in one story board square, and perhaps draw a sketch of the new and improved design.

Day 6 – Revision and Final Testing

Preparation:

- Make sure you have a fresh supply of 10g ice penguins. Since ice will sublimate over time and lose mass, it’s best to make a fresh batch each evening.

Step 1: Allow students to make revisions to their designs.

Step 2: Repeat the testing process as before. While the igloos are in the cooker, administer the post test to students. Collect these assessments and use them to see how effective the intervention was at helping students learn heat transfer conceptions. If students finish early, they can work to finalize their poster.

Step 3: Repeat the process of massing the penguin remains and recording the results on a chart for discussion. Any team which improves their design so that the amount of penguin mass remaining is more than before deserves acclaim for being an engineer. You can distribute awards as you see fit. You can give 1st, 2nd, and 3rd place awards, or simply award each team with an improved design. One award you could give out is to the team who came in the top 50% of the class but spent the least amount of money. This could be the Affordable Housing Award for Financially Challenged Penguins!

Have students record their final design and results on a story board square.

Step 4: Ask students what they liked and disliked about this unit. Use this information to help you plan future units which combine engineering design with science.
Step 5: Distribute awards. An award template is provided in this ETK. See Figure 15.

Figure 15. Award sample
Appendix B

Performance objectives for the engineering design-based heat transfer unit.

<table>
<thead>
<tr>
<th>BLOOM'S LEVEL</th>
<th>LEARNING OBJECTIVE</th>
</tr>
</thead>
</table>
| Knowledge     | Students will be able to define heat as the transfer of thermal energy.  
                | Students will be able to define conduction as the transfer of thermal energy through a solid material.  
                | Students will be able to define radiation as the transfer of thermal energy through space.  
                | Students will be able to define convection as the movement of a fluid from one place to another due to differences in density caused by differences in thermal energy. |
| Comprehension | Students will be able to predict that light colored or shiny objects reflect radiation better than dark objects; therefore they do not heat up much.  
                | Students will be able to describe that fluids expand when heated which makes them less dense, that less dense fluids have more buoyancy, so they tend to float above fluids with more density, and that when fluids cool, they contract which makes them denser.  
                | Students will be able to explain that when dark objects absorb radiation, this energy is transferred into thermal energy.  
                | Students will be able to explain why thermal energy moves from areas of higher temperature to areas of lower temperature. |
| Application   | Students will be able to apply knowledge that some materials are better than others at reducing the transfer of heat.  
                | Students will be able to demonstrate that materials that trap air reduce convection and reduce conduction.  
                | Students will be able to demonstrate that materials that are light colored or shiny reflect radiation.  
                | Students will be able to demonstrate that some materials are better conductors than others, i.e. metals conduct heat better than wood.  
                | Students will be able to demonstrate that some materials are better insulators than others, i.e. felt insulates better than foil.  
                | Students will be able to demonstrate that some materials are better at... |
reflecting radiation than others.

Analysis  Students will be able to explain how thermal energy transfers through solid materials as vibrating atoms collide with each other.

Students will be able to compare different materials to determine which ones are better at preventing heat transfer.

Students will be able to discern which type of heat transfer a material prevents.

Synthesis  Students will be able to combine information about different materials to synthesize a unique design.

Students will be able to create a device which reduces heat transfer and keeps an ice cube from melting.

Evaluation  Students will be able to evaluate devices designed to reduce heat transfer, compare them, and conclude how they work.

Students will be able to judge the effectiveness of devices designed to reduce heat transfer.
State and national standards met through the *Save the Penguin* ETK.

<table>
<thead>
<tr>
<th>STANDARD</th>
<th>GRADE LEVEL</th>
<th>CONTENT RELATED TO SAVE THE PENGUIN ETK</th>
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<tbody>
<tr>
<td>Virginia Standards of Learning</td>
<td>8th grade</td>
<td>Standard PS.7</td>
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<tr>
<td></td>
<td></td>
<td>The student will investigate and understand temperature scales, heat, and heat transfer. Key concepts include: conduction, convection, and radiation.</td>
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<td></td>
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<td>Atoms and molecules are perpetually in motion.</td>
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<td>The transfer of heat occurs in three ways: by conduction, by convection, and by radiation.</td>
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<tr>
<td><em>National Science Education Standards</em></td>
<td>Grades 5-8</td>
<td>Physical Science Content Standard B</td>
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<tr>
<td></td>
<td></td>
<td>1. Heat moves in predictable ways, flowing from warmer objects to cooler ones, until both reach the same temperature.</td>
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<td></td>
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<td>2. Light interacts with matter by absorption or reflection.</td>
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<tr>
<td><em>Benchmarks for Science Literacy</em></td>
<td>Grades 6-8</td>
<td>Chapter 4E</td>
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<tr>
<td></td>
<td></td>
<td>1. Heat can be transferred through materials by the collision of atoms or across space by radiation.</td>
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<td>2. If the material is fluid, currents will be set up in it that aid in the transfer of heat.</td>
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<td></td>
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<td>3. Heat energy is the disorderly motion of molecules.</td>
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Standards for Technological Literacy

Standard 8

Design is a creative planning process that leads to useful products and systems. There is no perfect design. Requirements for a design are made up of criteria and constraints.

Standard 9

Design involves a set of steps which can be performed in different sequences and repeated as needed. Brainstorming is a group problem-solving design process in which each person in the group presents his or her ideas in an open forum. Modeling, testing, evaluating and modifying are used to transform ideas into practical solutions.

Standard 10

Troubleshooting is a problem-solving method used to identify the cause of a malfunction in a technological system. Invention is the process of turning ideas and imagination into devices and systems. Some technological problems are best solved through experimentation.
Appendix D

Evaluation Survey

DO NOT PUT YOUR NAME ON THIS HANDOUT

Completion of this survey is voluntary. You do not have to complete the survey if you do not want to. You do not have to answer all the questions if you do not want to.

1.) How much did you learn from using the *Save the Penguins* kit (really)?

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2.) How much fun was this experience (really)?

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3.) How challenging was this experience?

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4.) How successful was your final product?

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5.) How much did you enjoy working in a team?

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6.) How much did everyone on your team contribute?

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7.) How well do you understand the concept of heat and how solar energy can be transformed into heat?

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8.) How well do you understand convection, conduction and radiation?

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9.) How well do you understand the design process?

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10.) Was your teacher effective at helping you learn science through engineering design?

11.) What was your teacher trying to teach you?

12.) What was the best part about this experience?

13.) What was the worst part about this experience?
Appendix E

ETK Exit Interview Protocol

Introduction: Our research is focused on how Engineering Teaching Kits can assist teachers in implementing effective science instruction. As a teacher who has used an ETK either alone or with engineering students from UVa, we are interested in your opinion about the kits. In this interview/survey, I’ll be asking you questions about how you think the ETK or ETKs you have used have impacted both your teaching and your students. 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 may leave it blank or simply not answer it. Participation in this study is voluntary.

Additionally, if you wish to withdraw from this study at any time, please notify

Christine Schnittka
Curry School of Education
PO Box 400273
Charlottesville, VA 22904-4273
(434) 996-7095
schnittka@virginia.edu

1. Which ETKs have been used in your classroom? Did the UVa engineering students teach the kit, or did you teach it yourself?
2. What do you think the effects were on student engagement while students participated in an ETK? (If you have used multiple ETKs, please provide an answer for each one.)
3. What do you think the effects were on student learning while students participated in an ETK? (If you have used multiple ETKs, please provide an answer for each one.)
4. Was there a particular group of students that the ETK or ETKs attracted or interested more?
5. How comfortable would you feel teaching by yourself with an ETK?
6. What do you see as the greatest benefit of the ETK or ETKs used in your classroom?
7. What frustrations, if any, did you experience as a result of the ETK?
Appendix F
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?
   a. Metals conduct heat better than wood.
   b. Wood conducts heat better than metals.
   c. Metals pull in heat because heat is attracted to metals.
   d. 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?
   a. Cool air is less dense than hot air.
   b. Warm air rises and cool air sinks.
   c. The upstairs rooms are closer to the sun.
   d. 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?
   a. Aluminum foil wrapped around the soda because metals transfer heat energy easily.
   b. A paper towel wrapped around the soda because paper soaks up the moisture.
   c. Wax paper wrapped around the soda because wax paper traps the moisture.
   d. 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?
    a. The heat radiates along the coat hanger.
    b. The heat builds up near the flame until it can’t hold it anymore and then moves along the coat hanger.
    c. Metal atoms vibrate with more energy when they get hot, and they collide with atoms near them, which makes the neighboring atoms vibrate too.
    d. 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,
    a. The plates have the same temperature.
    b. The plastic plate has a higher temperature.
    c. The plastic plate has a lower temperature.
    d. The aluminum plate has a lower temperature.

12. When placed in direct sunlight, which object will absorb the most radiation?
    a. a white sweater
    b. a snowball
    c. some aluminum foil
    d. a black sweater
Appendix G

Attitudes toward Engineering Survey

Read each question below, then, circle the ONE response that best expresses your attitude.

1. Engineering would be a highly interesting profession for me.
   1 2 3 4 5
   Strongly Disagree Neither agree Agree Strongly Disagree nor disagree Agree

2. Engineers spend most of their time doing complex mathematical calculations.
   1 2 3 4 5
   Strongly Disagree Neither agree Agree Strongly Disagree nor disagree Agree

3. Engineers design things that are practical and useful.
   1 2 3 4 5
   Strongly Disagree Neither agree Agree Strongly Disagree nor disagree Agree

4. Engineers spend relatively little time dealing with other people.
   1 2 3 4 5
   Strongly Disagree Neither agree Agree Strongly Disagree nor disagree Agree

5. Engineering is important to our country’s economic success in the world.
   1 2 3 4 5
   Strongly Disagree Neither agree Agree Strongly Disagree nor disagree Agree

6. Engineers don’t need to know much about environmental issues.
   1 2 3 4 5
   Strongly Disagree Neither agree Agree Strongly Disagree nor disagree Agree

7. Engineers don’t have to deal with questions about behavior that is morally right or wrong.
   1 2 3 4 5
   Strongly Disagree Neither agree Agree Strongly Disagree nor disagree Agree

8. Engineering skills are useful in everyday life.
   1 2 3 4 5
   Strongly Disagree Neither agree Agree Strongly Disagree nor disagree Agree
9. I would consider a career in engineering.

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10. To be a good engineer requires an IQ in the genius range.

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11. Engineers deal primarily with ideas, not practical uses for ideas.

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Appendix H

Teacher Entrance Interview Protocol

My research is focused on how students learn science. I’ll be asking you questions about how you plan to teach your unit on heat transfer. 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. Tell me a little bit about your science teaching history and experience. (How did you get to be a science teacher? How long have you been teaching? What attracted you to science?)

2. How do students best learn science? (Can you give an example of a lesson/unit that you taught where students really learned the concept?)

3. How would you define inquiry-based teaching for someone who is unfamiliar with the method?

4. What do you see as the benefits and drawbacks of inquiry-based teaching?

5. What kinds of struggles have you faced in implementing this inquiry-based teaching? What kinds of successes have you had?

6. What are the ways you have implemented inquiry-based science in your classroom? (Can you give an example of a really great inquiry-based lesson that you taught? How did it go? What would you do differently next time?)

7. What are your objectives or goals for this unit on heat transfer? (What do you hope all students will learn?)

8. How have you typically taught this unit on heat transfer?

9. What are your thoughts and feelings about the design-based “Save the Penguin” challenge that you will be using with the experimental class? (Do you have any concerns, worries, or apprehensions? Do you have a preconceived notion about how students will learn in one class compared to the other class?)
Appendix I

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 transfer, and how they feel about science and engineering. I’ll be asking you questions about what you know about heat transfer, 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 know about 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?)
2. [Ahead of time, choose up to three 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.) [1, 4, 7, 8]
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.) [3, 4, 5, 6, 7, 8]
5. Do you like learning science in school? (Probe: What about it do you like or dislike?)
6. Do you know anyone who is an engineer? (Probe: Who, and what have they told you about engineering?)
7. What do you think engineers do?
8. What do you think engineers are like?
9. Would you like to be an engineer? (Probe: Why? What do you imagine yourself doing?)

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Appendix J

Student Exit Interview Protocol

My research is focused on how students learn about heat transfer, and how they feel about science and engineering. I’ll be asking you questions about what you have just learned about heat transfer 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 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 heat transfer? Probe: Ask pupils to apply the lessons/activities to the specific concept.
3. Overall, did you enjoy this unit on heat transfer? What did you like about the unit? What did you not like about it?
4. [Ahead of time, choose up to three questions from the pre- and 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 a younger cousin or sibling. 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.) [1, 4, 7, 8]
6. If you are outside at the beach on a very hot day and you want to keep your can of soda cold, what are some things you can do to keep it cold? (Probe: give students hints about what materials they may have nearby by showing them a list and pictures—an umbrella, a beach towel, a beach chair, sand, a bucket, ocean water... tell them they can be creative. Ask them to justify their answer with scientific reasons.) [3, 4, 5, 7, 8]
7. What kind of heat transfer would that component prevent? Why?)
8. Do you like learning science in school? (Probe: What about it do you like or dislike?)
9. Do you know anyone who is an engineer? (Probe: Who, and what have they told you about engineering?)
10. What do you think engineers do?
11. What do you think engineers are like?
12. Would you like to be an engineer? (Probe: Why? What do you imagine yourself doing?)
13. (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.)
Appendix K

Teacher Exit Interview Protocol

My research is focused on how students learn science. I’ll be asking you questions about how you taught your unit on heat transfer. 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 are your objectives or goals for this unit on heat transfer? (What did you hope all students would learn?)

2. Do you think all your classes achieved these goals? (What do you think students got out of the instruction? What evidence do you have for your answer?)

3. Do you think that any one class learned the science concepts better than another? Why?

4. How did you use inquiry with each of the classes? Were the inquiry activities successful? What benefits and/or frustrations did you have with these inquiry activities?

5. Did you see a difference in student engagement between your classes? (If there was a difference, why do you think it existed? If there was not a difference, how do you see each approach as equally engaging? What evidence do you have for student engagement?)

6. Did you see a difference in student motivation between your classes? (If there was a difference, why do you think it existed? If there was not a difference, how do you see each approach as equally motivating? What evidence do you have for student motivation?)

7. Was there a particular group of students that the Save the Penguins activity attracted or interested more? Why do you think so?

8. Was there a particular group of students that the typical method attracted or interested more? Why do you think so?

9. In the future, how will you teach this unit on heat transfer? Why?

10. What are your thoughts and feelings about the design-based “Save the Penguin” challenge that you used with the experimental class? (Did you see any drawbacks to using the challenge? Do you have any suggestions for improving the curriculum?)

11. What do you see as the greatest benefit of using design challenges in your classroom?

12. What frustrations, if any, did you experience as a result of using a design challenge in your classroom?