Contents

Teaching Engineering Concepts in High School Project

A key development for technology and engineering education is the recent release of the National Research Council 2011 report, *A Framework for K-12 Science Standards.* While the new directions in science education may trigger concern for some, it is nevertheless important to pay attention to this important development. Another perspective is that this sends a positive signal, validating the value and importance of engineering and design within science education and, by extension, to STEM across the K-12 spectrum. The development of the next generation of science standards will generate considerable activity including curriculum and professional development, as well as some rethinking of science pre-service teacher education. This significant activity within the STEM education community should be of interest to technology and engineering educators. It is important that we be aware and engaged in a variety of ways.

We have been asked to share information about a recently funded National Science Foundation (NSF) project designed to explore science teachers' understanding of engineering concepts and the extent to which engineering can facilitate science learning. The project will help inform the teaching and learning of engineering within science, which represents an important component of the *Science Framework* and also, more broadly, across the STEM education spectrum.

The project is collaboration between Black Hills State University, Purdue University, University of Maryland-Baltimore County, Stevens Institute of Technology, and University of Massachusetts-Boston. We will examine the viability of an engineering concept based approach to teacher professional development within life and physical science by: (a) refining the conceptual base of engineering for secondary level learning, (b) developing teachers' understanding of engineering concepts, (c) engaging the teachers in a process of curriculum concept infusion, and (d) studying the change in teachers' understandings and impact on learning and teaching. Research will be conducted to understand how science teachers learn engineering concepts and the issues and problems encountered during implementation.

This project stems from the principal investigators' research on engineering teacher professional development (Daugherty, 2009; Daugherty & Custer, 2010; Daugherty, 2009; Ross & Bayles, 2007). Case studies of five of the most prominent teacher professional development projects focused on engineering education were conducted with one of the primary findings being a distinct lack of grounding in an identified engineering concept base. One of the most alarming aspects of this void was the teachers' inability to reflect on what they were learning related to engineering, apart from a vague understanding of the engineering design process. Without a clear understanding of core engineering content and concepts, the connection to student learning is tenuous at best. This void also poses serious problems for high quality curriculum and professional development as has been documented in the science and mathematics teacher professional development literature (Garet, Porter, Desimone, Birman, & Yoon, 2001; Guskey, 2003; Supovitz & Turner, 2000). As the National Academy of Engineering Committee on K-12 Engineering Education observed, a "critical factor is whether teachers—from elementary generalists to middle school and high school specialists—understand basic engineering concepts and are comfortable engaging in, and teaching, engineering design" (Katehi, Pearson, & Feder, 2009, p. 71-72).

An important facet of the design of the professional development is the inclusion of a few of carefully selected engineering/technology teachers in the cohort of teachers who have expertise in design-based curriculum, active student learning, and assessment. This will enable us to tap into their expertise specific to the incorporation of engineering into the curriculum. We will explore the impact of their involvement on science teachers' learning and engagement with the engineering concepts. This information will be potentially important as we eventually seek to better understand how to facilitate the engagement of science teachers with engineering concepts and processes. We will also seek examine how the engineering/technology teachers engage with the science content that will be presented in the professional development.

This project seeks to develop and research teacher learning through an innovative approach to professional development that is concept-driven. Through targeted partnerships, the team will develop an engineering concept based professional development approach and examine its viability. Specifically, the goals are:

- To understand how science teachers learn engineering concepts through a concept-based professional development program.
- To examine the implementation issues and problems encountered by teachers as they incorporate engineering concepts into standards-based curricula and instructional activities.
- To explore ways in which engineering can inform and facilitate the learning of science concepts.

We look forward to learning from (and about) our science colleagues and to extending that learning to the larger STEM education communities. More important, we hope that our work will ultimately help to engage more students with exciting engineering concepts and activities to achieve important learning outcomes.

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This was an invited article.

Articles

The $GRID_C$ Project: Developing Students' Thinking Skills in a Data-Rich Environment

The purpose of this study was to determine the impact of using renewable energy data, obtained from a comprehensive data acquisition system, on improving students' learning and developing their higher-order learning skills. This study used renewable energy data available through a data acquisition system installed and tested by the ***G***reen ***R***esearch for ***I***ncorporating ***D***ata in the ***C***lassroom ($GRID_C$) project. The purpose of $GRID_C$ is to develop curriculum to teach science, technology, engineering, and mathematics (STEM) concepts using data collected from renewable energy technologies at the North Carolina Solar House (NC Solar House), located on the campus of North Carolina State University (NC State). This project enhances instruction and improves learning while addressing a highly relevant social issue—renewable energy. The $GRID_C$ project gives professors, instructors, and their students the opportunity to study and evaluate the value of renewable energy systems through the use of real-time renewable energy data.

Throughout the years, researchers have shown the value of using real world data to enhance instruction in mathematics, science, and social studies (Drier, Dawson, & Garofalo, 1999; Gordin, Polman, & Pea, 1994). Climate and environmental databases, such as the Quantitative Environmental Learning Project website (Langkamp & Hull, 2002), are available to educators to support instruction. Curricula that are based on the performance data of renewable energy technologies provide students with valuable knowledge and skills that can be used for professional growth and decision making. Data-driven decision making is a critical skill used in engineering and education (Diane, Johnson, & Mistry, 2004; Mandinach, Honey, Light, Heinze, & Rivas, 2005), and as technological and social systems become more complex, the aptitude for data-driven decision making becomes even more critical.

In order to develop students' higher order thinking skills in the context of a data-rich learning environment, the researchers considered that students must understand factual, conceptual, and procedural knowledge; apply their knowledge to learn by doing; and then reflect on the process that led to the solution (Bransford, Brown, & Cocking, 2000; Anderson, Krathwohl, Airasian, Cruikshank, Mayer, Raths, & Wittrock, 2001).

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Factual and conceptual knowledge includes an understanding of the systems, subsystems, and components of the technology being studied. In other words, what is the basic design, how does it function, and what are the expected outputs? This knowledge, gained through lecture, readings, or personal research, forms the basic understanding needed before proceeding with the design and problem-solving process (Lumsdaine, Shelnutt, & Lumsdaine, 1999).

Procedural knowledge includes an understanding of the engineering design and/or problem-solving processes that lead to innovative solutions. The processes and strategies used to solve problems and make decisions must be understood (Schweiger, 2003; Woods, 2000). These processes include equations used to calculate system performance, transform data, and make predictions and problem-solving processes, such as troubleshooting and project management, that help engineers, designers, and technicians reach solutions.

However, in order to develop higher order thinking skills, students must have the opportunity to apply their content and process knowledge (Bonanno, 2004; Moriyama, Satou, & King, 2002; DeLuca, 1992) and learn from errors (Mathan & Koedinger, 2005). Performance data from the variety of renewable energy systems proposed for this project provide opportunities for students and teachers to analyze and evaluate system variables within the context of their disciplines.

Bransford, Brown, and Cocking (2000) discuss the importance of making students' thinking visible. The nature of the data collected and used in this study supports the development of thinking skills and allowing students to reflect on their thought process. Students have the opportunity to analyze, evaluate, and predict while applying concepts in a variety of situations. Reflection also includes looking back on the processes that led to decisions (Quintana, Zhang, & Krajcik, 2005). The $GRID_C$ project team and participating professors and instructors developed instructional units grounded in these concepts while incorporating the use of the renewable energy data collected through $GRID_C$ resources into the units.

The core of the $GRID_C$ data acquisition system is located at the NC Solar House and gathers renewable energy data from the house and other units (e.g., garage and research annex) on the grounds. The NC Solar House was first opened to the public in 1981 and is one of the most visible/well-known and visited solar buildings in the United States today.

The monitoring system records meteorological data (i.e., irradiance, ambient and module temperature, wind speed and direction, module temperature, relative humidity, rain gauge, barometric pressure), photovoltaic data (i.e., AC/DC power, current, voltage, and energy, panel temperature), hot water data (i.e., flow rate, in/out temperate, energy), and hydrogen fuel cell data (i.e., in/out power, current and voltage, energy).

Data from these systems is collected and uploaded to an online data acquisition system, where daily, monthly, and yearly information may be viewed graphically or downloaded in a spreadsheet format. The aggregated $GRID_C$ data, available on the project's website (www.$GRID_C$.net), is used by professors and instructors to develop instructional units to be implemented in various undergraduate and graduate level courses.

Method

Participants

The sample consisted of 118 individuals. Student data was collected from a variety of undergraduate and graduate courses at NC State and a course at Pitt Community College. The research team gathered student data through each course's professor or instructor and assigned a number to each student, which was subsequently used in data analysis. This allowed for full student confidentiality. Students were selected based on their enrollment in engineering, STEM education, or construction courses that addressed topics in renewable energy. Specifically, the students were enrolled in one of the following courses:

- Construction Technology (TED 221 – Undergraduate Course – Department of Mathematics, Science, and Technology Education, College of Education, NC State): This course provides an overview of residential and commercial structures and their construction. Students use drawings and models completed in a laboratory environment to simulate construction methods.
- Current Trends in Technical Graphics Education (TED 532 – Graduate Course – Department of Mathematics, Science, and Technology Education, College of Education, NC State): This graduate level course discusses the current trends in technology, techniques, and theories relating to technical graphics education. The course is centered on assigned readings and student-researched presentations on topical subjects; readings are drawn from journals and texts, on-line databases and articles, and current news media sources.
- Instructional Science Materials (EMS 373 – Undergraduate Course – Department of Mathematics, Science, and Technology Education, College of Education, NC State): This course teaches students to develop and select teaching materials that reflect concepts of content, with an emphasis on middle and secondary school science. The course provides an overview of experimental and laboratory approaches, including the use of microcomputer and video technologies.
- Design of Solar Heating Systems (MAE 421 – Undergraduate Course – Department of Mechanical and Aerospace Engineering, College of Engineering, NC State): This course involves the analysis and design of active and passive solar thermal systems for residential and small commercial buildings. The course provides an overview of solar insulation, flat plate collectors, thermal storage, heat exchanges, controls, performance calculations, suncharts, and photovoltaics.

- Selected Topics in Energy Efficient Building and Design (CST 293 – Construction and Industrial Technology Division, Pitt Community College): This course familiarizes students with building principles that form the basis of energy efficient building and design. Students will be exposed to passive solar design, thermal analysis, indoor air quality, and studying the house as a system.

Given the mix of community college students and university students enrolled in lower and upper level courses, subjects varied in age and class rank. The instructional modules developed were reviewed to ensure that they broadened opportunities and enabled the equitable participation of women, nontraditional age groups, underrepresented minorities, and persons with disabilities.

North Carolina's Community College System has, throughout its history, served nontraditional age groups through its successful outreach to adults seeking education, training, and retraining for the workforce, including basic skills and literacy education, as well as occupational and pre-baccalaureate programs. The 58 North Carolina community colleges reported over 810,000 curriculum and continuing education student enrollments for the 2007-2008 academic year. Among the nearly 300,000 curriculum student enrollees, females outnumbered males approximately 2 to 1 (NCCCS, 2008a). Racial diversity is also noteworthy: 24.9% of the student population is black, 1.5% American Indian, 2.1% Asian, and 3.6% Latino. At Pitt Community College, with over 9,000 curriculum students enrolled, approximately 31% are black, 0.5% American Indian, 1.1% Asian, and 2.1% Latino (NCCCS, 2008b).

Instruments

Each instructional unit was developed and implemented by the professor or instructor assigned to the course. The $GRID_C$ project team provided individual training sessions for the professors and instructors involved in curriculum development and design. Each session included a detailed description of the project's curriculum design goals and involved discussions on factual, conceptual, and procedural knowledge; knowledge application; and student reflection. Handouts were provided on methodology, instrumentation, procedure, and assessing learning outcomes. The sessions gave professors and instructors a good opportunity to ask questions. Instructional units were designed to use the $GRID_C$ renewable data, presenting students with problems pertaining to renewable energy issues. Students were exposed to the website and required to download and manipulate data to answer questions.

To determine if the desired learning objectives were achieved, the following research method was employed. Each unit began with a pretest consisting of general renewable energy knowledge items and a metacognitive inventory. With the introduction of each unit, students were instructed on the unit's learning objectives and required activities. During the unit, students kept a journal. Upon completion of each unit, the posttest knowledge questions and the metacognitive inventory were administered. Data collected with pre-/post-tests, journals, forums, and activities requiring knowledge application were archived for statistical analysis and reporting.

Thus, three instruments were designed and used to measure knowledge, application, and reflection. Knowledge gained was measured through pre- and post-test analysis. Alternative versions of a multiple choice test were developed by a panel of content experts. Each test consisted of a set of core questions (i.e., common questions across disciplines) as well as discipline-specific questions.

Application of knowledge gained in the units developed was measured through certain activities, and rubrics were developed to measure student performance on assigned activities. Once again, a panel of content experts was used to develop the rubrics, and a separate panel was used to validate the measure. Post-analysis was done to determine reliability and to ensure continuous improvement. Finally, to measure reflection, quantitative and qualitative analyses were conducted on student journals.

Students' awareness of their cognitive processes as they approach and solve problems was evaluated using the metacognitive inventory. The Metacognitive Inventory (MI) was developed using 6 items from the Problem-Solving Inventory (PSI) and 20 items from the State Metacognitive Inventory (SMI), with slight modifications (Heppner, 1994; O'Neil & Abedi, 1996). This inventory was designed such that it may be used in varied situations in which the developed curricula are implemented. The items cover the six categories of *approach-avoidance*, *awareness*, *cognitive strategy*, *confidence*, *planning*, and *self-checking*. The Appendix provides a list of items within each category; items derived from the PSI are marked accordingly. The PSI is a 35-item test, which uses the Likert scale response options to assess individuals' awareness of their style of solving life problems such as relationship conflicts and career choices (Heppner, 1994). The SMI, a 20-item test which also makes use of Likert scale response options, is used to assess the extent to which students are aware of thinking skills they use to complete tests (O'Neil & Abedi, 1996).

Results

The first unit was implemented in the fall semester of 2008. Since then, units have been implemented and data gathered from five other classes, providing 118 observations. Several observations were deleted for certain analyses; these deletions are detailed on the next page.

Renewable Energy General Knowledge Outcomes

In one course, the instructor failed to administer the renewable energy general knowledge posttest questions, leaving researchers with a base of 112 observations. Table 1 provides descriptive statistics for the renewable energy general knowledge pre- and post-tests. The tests were graded out of 12 possible points.

Table 1
Descriptive Statistics for the Renewable Energy General Knowledge Pre- and Post-Tests

	Mean	Std Deviation	Minimum	Maximum	Median
General Knowledge Pretest	6.33	2.06	1.71	11	6.6
General Knowledge Posttest	8.25	1.85	2.4	11.4	8.57

Table 2 presents the results of the Shapiro-Wilk test for normality. The null hypothesis is that the data are normally distributed.

Table 2
General Knowledge – Normality Assumption Checks (Results of Shapiro-Wilk Test)

	Statistic (W)	df	Sig.
Difference in General Knowledge Pre- and Post-Tests	0.986	97	0.391

The null hypothesis was not rejected, and the normality assumption was satisfied. A paired t-test is used for the analysis. The results indicate significant gains in posttest renewable energy general knowledge scores ($t(96) = 9.41$, $p < 0.001$).

Metacognitive Inventory Outcomes

Table 3 (next page) provides descriptive statistics for the MI pre- and post-tests. Administration error resulted in the loss of 50 of the 118 observations in the analysis of the MI and its individual items.

Table 3
Descriptive Statistics for the Metacognitive Inventory (MI) Pre- and Post-Tests

	Mean	Std. Deviation	Minimum	Maximum	Median
MI Pretest	3.98	0.41	2.85	4.96	3.96
MI Posttest	4.07	0.45	2.92	5	4.04

Table 4 presents the results of the Shapiro-Wilk test for normality. The null hypothesis was that the data were normally distributed.

Table 4
MI – Normality Assumption Checks (Results of Shapiro-Wilk Test)

	Statistic (W)	df	Sig.
Difference in General Knowledge Pre- and Post-Tests	0.987	59	0.784

The null hypothesis was not rejected, and the normality assumption was satisfied. A paired t-test was used for the analysis. The results indicated significant gains in metacognitive performance, as measured by the MI ($t(58) = 2.19$, $p < 0.001$).

A Wilcoxon signed-rank test was performed on each of the 26 MI items. The MI made use of 5-point Likert scale response options. Six items showed significant gains in student perceptions, primarily in items from the category of "self-checking." Table 5 provides descriptive statistics for the items found significant under the category of "self-checking."

Table 5
Descriptive Statistics for Significant "Self-Checking" Items

Item		Mean	Std. Deviation	Min	Max	Median
After I solve a problem, I analyze what went right or what went wrong.	Pre Post	3.95 4.17	0.76 0.68	1 2	5 5	4 4
I almost always know how much of an assignment I have left to complete.	Pre Post	3.86 4.06	0.66 0.77	2 3	5 5	4 4
I check my accuracy as I progress through assignments.	Pre Post	3.69 3.96	0.78 0.76	2 1	5 5	4 4

Table 6 presents the results of Wilcoxon signed-rank tests. In the category of "self-checking", the items “After I solve a problem, I analyze what went right or what went wrong,” “I almost always know how much of an assignment I have left to complete,” and “I check my accuracy as I progress through assignments” showed significant gains from pre- to post-tests.

Table 6
Wilcoxon Signed-Rank Test Results for "Self-Checking" Items

Item	Signed Rank
After I solve a problem, I analyze what went right or what went wrong.	76.5**
I almost always know how much of an assignment I have left to complete.	99.0*
I check my accuracy as I progress through assignments.	122.0**

Where * indicates significance at $p < 0.05$ and ** indicates significance at $p < 0.01$.

Table 7 provides descriptive statistics for the items found significant under the categories of "confidence," "cognitive strategy," and "awareness."

Table 7
Descriptive Statistics for Significant "Confidence," "Cognitive Strategy," & "Awareness" Items

Item		Mean	Std. Deviation	Min	Max	Median
I am usually able to think up creative or effective alternatives to solve a problem.	Pre	4	0.71	2	5	4
	Post	4.20	0.67	3	5	4
I think through the meaning of assignments before I begin.	Pre	3.5	0.93	2	5	4
	Post	3.86	0.81	2	5	4
I am aware of which thinking techniques and strategies to use and when to use them.	Pre	3.69	0.69	2	5	4
	Post	4	0.73	2	5	4

Table 8 (next page) presents the results of Wilcoxon signed-rank tests. The following items from the category of "awareness" also indicated significant gains: “I am usually able to think up creative or effective alternatives to solve a problem” from the category of "confidence," “I think through the meaning of assignments before I begin" from the category of "cognitive strategy," and "I am aware of which thinking techniques and strategies to use and when to use them."

Table 8
Wilcoxon Signed-Rank Test Results for "Confidence," "Cognitive Strategy," & "Awareness" Items

Item	Signed Rank
I am usually able to think up creative or effective alternatives to solve a problem.	82.0**
I think through the meaning of assignments before I begin.	147.0**
I am aware of which thinking techniques and strategies to use and when to use them.	182.0***

Where * indicates significance at $p < 0.05$, ** indicates significance at $p < 0.01$ and ***indicates significance at $p < 0.001$.

Table 9 provides descriptive statistics for the significant item under "awareness."

Table 9
Descriptive Statistics for "Awareness" Item

Item		Mean	Std. Deviation	Min	Max	Median
I am aware of the need to plan my course of action.	Pre	4.39	0.66	2	5	4
	Post	4.13	0.70	3	5	4

Surprisingly, the following item from the category of awareness showed a decrease in perceived frequency of use: "I am aware of the need to plan my course of action."

Table 10 presents the results of the Wilcoxon signed-rank test.

Table 10
Wilcoxon Signed-Rank Test Results for "Awareness" Item

Item	Signed Rank
I am aware of the need to plan my course of action.	(-) 96.0*

Where * indicates significance at $p < 0.05$

Reliability of Metacognitive Inventory Items

The MI consists of six categories. The categories of "awareness," "cognitive strategy," "planning," and "self-checking" consist of six items each, and the categories of "approach/avoidance" and "problem-solving confidence" consist of three items each. Cronbach’s alpha was used in subsequent analyses to estimate the internal consistency for each of the categories. Alpha coefficients for the categories of "awareness," "cognitive strategy," "planning," and "self-checking" indicate a good scale ($\alpha \geq 0.75$). Cronbach’s alpha decreases as the number of items in the category decreases, which may explain the lower alpha values for the categories of "problem-solving confidence" and "approach/avoidance style," 0.57 and 0.63, respectively. However, given the smaller number of items in these categories, alpha for "approach/avoidance" still proves adequate.

Discussion

The present analyses show significant gains in posttest renewable energy general knowledge scores. This indicates that the use of real-time renewable energy data was effective in instruction, providing students with valuable knowledge and skills that can be used for decision making. The results confirm the claims of previous studies that using real world data enhances instruction in various fields.

The researchers also found significant gains in metacognitive performance, as measured by the metacognitive inventory. The metcognitive inventory makes the thinking process visible, thereby allowing researchers to see the significant increase in students’ reflections on their thought processes. This outcome is of particular importance, as research on technological problem solving, critical thinking, novice/expert performance, and metacognition has shown that students must understand factual, conceptual, and procedural knowledge; apply their knowledge to learn by doing; and then reflect on the process that led to the solution (Bransford, Brown, & Cocking, 2000; Anderson, Krathwohl, Airasian, Cruikshank, Mayer, Raths, & Wittrock, 2001).

Detailed analyses of the MI showed significant gains for certain items. The majority of gains were in the category of "self-checking." Students were found to check the accuracy of their work as they progressed through assignments and reflect on problems, analyzing what went right or what went wrong. Further, they developed a better understanding of how much of an assignment they had left to complete.

Significant gains were found in other MI categories as well. Students reported a greater ability to think up creative or effective alternatives to solve a problem, which showed a significant increase in the area of "confidence." They also reported thinking through the meaning of assignments before beginning, showing development of a "cognitive strategy." Finally, in the category of "awareness," students reported becoming more aware of which thinking techniques and strategies to use and when to use them. However, within the same category of "awareness," students showed a decrease in awareness of their need to plan a course of action. Collection of more data will allow for a deeper evaluation of these statements and explorations of how general knowledge and MI outcomes may differ among various demographic groups.

To this end, $GRID_C$ researchers are actively recruiting professors and instructors from various NC State departments, local colleges and universities, and K-12 teachers to help develop and implement $GRID_C$ curricula. In an effort to obtain quality data with a maximum number of usable observations, steps have been taken to ensure that professors and instructors are aware of the importance and value of proper data collection.

In addition to gathering more student data, the future brings new opportunities for collaboration with various companies within the energy and transportation industries. Such collaboration will expand $GRID_C$'s data acquisition system to include transportation data, as well as wind energy data. Broadening the data acquisition system will further enhance students' opportunities to conduct comparative analysis and aggregate data for decision making.

Finally, refinements to the curriculum will be introduced to demonstrate the effectiveness of an integrated, data-rich curriculum to teach STEM concepts and develop metacognitive skills. Through the various courses offered among the partnering institutions, this curriculum will reach a sizeable and diverse population of science, engineering, and technology students, better enabling students to learn about renewable energy technologies by understanding the variables and variable relationships that are controlled by the technologies' design and function. Additionally, students will learn how the disciplines of science and mathematics are used in the design and optimization of systems. As the results suggest, the $GRID_C$ research project has national implications for improving STEM education and will provide a platform for continued research and development of instructional materials that improve STEM education.

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Appendix

Awareness

I am aware of the need to plan my course of action.
I am aware of my ongoing thinking processes.
I am aware of my own thinking.
I am aware of my trying to understand assignments before I attempt to solve them.
I am aware of which thinking techniques and strategies to use and when to use them.

Cognitive Strategy

I think through the meaning of assignments before I begin.
I use multiple thinking techniques or strategies to complete an assignment
I attempt to discover the main ideas in assignments.
I select and organize relevant information to complete assignments.
I ask myself how the assignments are related to what I already know.

Planning

I try to determine what assignments require.
I make sure I understand just what has to be done and how to do it.
I determine how to solve assignments.
I try to understand the goals of assignments before I attempt to answer or solve.
I try to understand assignments before I attempt to solve them.

Self-Checking

I almost always know how much of an assignment I have left to complete.
I keep track of my progress and, if necessary, change my techniques or strategies.
I check my work while I am doing it.
I check my accuracy as I progress through assignments.
I correct my errors.

Problem-Solving Confidence
I trust my ability to solve new and difficult problems. (PSI)
I am usually able to think up creative or effective alternatives to solve a problem. (PSI)
When I become aware of a problem, one of the first things I do is to try to find out exactly what the problem is. (PSI)

Approach/Avoidance Style
After I solve a problem, I analyze what went right or what went wrong. (PSI)
When confronted with a problem, I stop and think about it before deciding on a next step. (PSI)
In trying to solve a problem, one strategy I often use is to think of past problems that have been similar. (PSI)

Analysis of Engineering Content within Technology Education Programs

Technology Education's Inclusion of Engineering

In the mid-1980s, technology education began to evolve from industrial arts curriculum (Lewis, 2004). Several developments in the field helped promote the technology education curriculum movement, including the Jackson's Mill Curriculum Theory Project (Snyder & Hales, 1981), the Standards for Technology Education Project (Dugger, 1985), and the development of a Conceptual Framework for Technology Education (Savage & Sterry, 1990). Since this evolution, technology educators have struggled to promote a human productive practice as a legitimate school subject, with the intent of producing technologically literate students (Lewis, 2005). The change of name and content to technology education was just another in a series since the inception of the practice. Previous industrial arts and technology education curriculum and content framing efforts in the United States include the Industrial Arts Curriculum Project, Maryland Plan, Jackson's Mill, and Technology for All Americans Project (Hill, 2006). The current movement involves incorporating engineering design as a focal point for technology education. Some technology education leaders believe that the incorporation of engineering in technology education will lead to greater technological literacy and promote engineering as a career choice (Lewis, 2005).

It is important to recognize the differences between technology and engineering. Technology can be defined as any modification of the natural world done to fulfill human needs or desires (Garmire & Pearson, 2006). Technology education, therefore, can be seen as the study of the history of technology, positive attributes and consequences of technology, and the development of the ability to use, manage, evaluate, and understand technology. Broadly stated, this is the definition of technological literacy. Engineers, on the other hand, are the people responsible for designing the technologies that modify the world. Engineering is a systematic and often iterative approach to designing objects, processes, and systems to meet human needs and wants (National Research Council, 2011).

The motivation for adding engineering content into the existing K-12 educational system is strong and continues to gain momentum (Katehi, Pearson, & Feder, 2009). There are many reasons for increased interest in K-12 engineering. Starting with the most general, the 21st century world is an environment designed for human comfort. Buildings, clothes, cars, clean water,

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indoor climate control, personal technologies, and nearly everything else people encounter in daily life are designed by the engineering community, which focuses on meeting the needs of society. Citizens need to be literate in technology and familiar with the engineering behind these technologies in order to make informed and responsible decisions. Adding engineering to the K-12 educational system will help create a technologically literate society (Pinelli & Haynie, 2010).

Similar to products or goods, engineering affects the economic health of the country. It is a national resource needed to be competitive with other countries in an increasingly technologically competitive atmosphere (Augustine, 2005). Technological innovations are a direct result of the work done by engineers. Engineers translate their understanding of fundamental science and mathematics into usable objects and applications that improve our lives, create new jobs and industries, and extend the frontiers of human possibility. The addition of engineering in secondary curriculum will help feed the engineering pipeline by exposing students to engineering content during their middle school and high school years (Pinelli & Haynie, 2010).

From a pedagogical perspective, engineering is the link that ties together mathematics and science (Katehi, et al., 2009). By providing context to the content, engineering and the engineering design process can bring to life sometimes abstract, difficult topics. Research shows that the integrative, applied nature of engineering can enhance student learning, boost test scores, and help schools meet standards-driven education requirements (Baker, 2005; Silk, Schunn, & Strand Cary, 2009). The use of engineering design provides practical classroom benefits for both educators and students. The collaborative, socially beneficial aspects of engineering have also been shown to appeal to students whom the field has traditionally failed to engage, including females and underrepresented minorities (Geddis, Onslow, Beynon, & Oesch, 1993; Wiest, 2004).

The purposeful move to include engineering was evidenced in 2009 by the International Technology Educators Association (ITEA) changing its name to the International Technology and Engineering Educators Association (ITEEA) (NRC, 2009). Following suit, the flagship technology education practitioner's journal, *The Technology Teacher*, also changed its name to *The Technology and Engineering Teacher*. Researchers are also very interested in methods and the effects of including engineering in the curriculum. After examining published research in prominent engineering journals and conferences, Williams (2011) found that the topics "design" and "curriculum" (including engineering in the curriculum) were the first and second most researched topics (Williams, 2011). Technology teachers in the field have also embraced the idea of including engineering into technology curriculum. This is demonstrated by the development of several technology education courses that promote pre-engineering, such as Project ProBase's Principles of Engineering and Project

Lead the Way's Principles of Technology, Engineering Technology, and Introduction to Engineering (Dearing & Daugherty, 2004).

Teacher Preparation

In order to effectively teach engineering, technology teachers need to be taught engineering content, concepts, and related pedagogy (Dearing & Daugherty, 2004; Fantz, De Miranda, & Siller, 2011). Some researchers posit that technology education programs may not have enough content to prepare technology teachers to teach engineering design (McAlister, 2005). Certain technology teacher education programs have responded by changing the programs' name to include engineering. However, a change of name does not necessarily indicate a change of content or pedagogy offered by the institutions. Therefore, this study is aimed at examining the differences between technology education programs that have adopted engineering into their name and those that have not. These technology education programs should not be confused with programs aimed specifically at studying methods of engineering education, such as Purdue University's and Virginia Tech's engineering education programs.

Research Questions

To determine the differences between traditional technology education programs and newer programs that have engineering embedded within their title, the authors developed two research questions.

1. Is there a different amount of engineering content between technology programs with the term "engineering" in their program title and technology programs without it?
2. Is there a different amount of engineering content between technology programs housed in engineering colleges and technology programs housed in colleges other than engineering?

Methodology

The data for this investigation is made up of undergraduate licensing technology education programs in US colleges and universities. The search for programs began with the list of 49 International Technology and Engineering Educators Association (ITEEA) institutional members (ITEEA, 2010). The website for each institution was visited and searched for a description of the technology education program. It should be noted that the websites were visited in the fall of 2010. This study is a snapshot in time of these technology education programs and may include some programs that were in the process of transitioning toward the inclusion of engineering, but had not yet changed titles, course names, or content. Due to the nature of the study and access restrictions, the data collection was limited to online catalogs and program descriptions. Eight technology education programs with engineering anywhere in the title were identified and included in the study. To gain more insight into the types of courses for each program, online college and university catalogs describing the graduation requirements for a bachelor's degree in technology education and associated course titles were searched and downloaded into a database. For comparison, eleven technology education programs housed in various colleges that did not have engineering in their title were selected at random. See Table 1(continued onto next page) for the list of all institutions investigated in this preliminary study. Institutions 1-8 have technology education licensing programs with engineering in the program title. Institutions 8-19 have technology education programs without engineering in the title.

Table 1
Technology Education Programs Included in the Preliminary Study

	College/University	Title of Program	Housed In
1	Central Connecticut University	Technology & Engineering Education	School of Engineering
2	Colorado State University	Engineering Education	College of Engineering
3	Eastern Kentucky University	Engineering/Technology Education	College of Business
4	Indiana State University	Technology and Engineering Education	College of Technology
5	North Carolina State University	Technology, Engineering & Design Education	College of Education
6	Purdue University	Engineering/Technology Teacher Education	College of Technology
7	The College of New Jersey	K-12 Pre-Engineering Education	School of Engineering
8	Utah State University	Engineering and Technology Education	College of Engineering
9	Appalachian State University	Technology Education	College of Fine and Applied Arts
10	Ball State University	Technology Teacher Education	College of Applied Sciences and Technology
11	Bowling Green State University	Technology Education Program	College of Technology

12	Buffalo State College	Technology Education	Technology Department
13	California University of Pennsylvania	Technology Education	Applied Engineering and Technology Department
14	Pittsburg State University	Technology Education	College of Technology
15	Rhode Island College	Technology Education	Department of Education
16	St. Cloud State University	Technology Education	College of Science & Engineering
17	State University of New York (Oswego)	Technology Education All Grades	School of Education
18	University of Arkansas	Technology Education	College of Education
19	University of Central Missouri	Technology Education	College of Education

A database was created to categorize where the technology education program is housed and the number of credit hours of engineering coursework. A course was considered to have engineering content if the word "engineering" was present in the course title or catalog description of the course. Other courses that are typically found in Accreditation Board for Engineering and Technology (ABET) accredited engineering programs, such as statics, dynamics, and mechanics of materials, were also defined as engineering coursework. Other foundational courses such as physics, chemistry, and mathematics were not counted as having engineering content. While not all-inclusive, Table 2 shows the most common course titles in the programs included in this study and how they were categorized. The number of credits for engineering related coursework and the number of credits for technology related coursework were entered into a spreadsheet, as shown in Table 3. The program was identified as being housed in a college of engineering if the term engineering was used anywhere in the college's title. The categorization of where the programs are housed is also shown in Table 3.

Table 2
Engineering vs. Non-Engineering Course Titles

Engineering Course Titles	Non-Engineering Course Titles
Civil Engineering and Architecture	Automated Systems
Dynamics (Engineering Mechanics II)	CAD
Electrical Engineering	Communications
Engineering Design	Construction
Engineering Math	Electricity/Electronics
Mechanics and Strengths of Materials	Energy and Power
Mechatronics	Graphics
Orientation to Engineering	Manufacturing
Statics (Engineering Mechanics I)	Production
Thermodynamics and Fluid Systems	Publishing
	Transportation

Table 3
Number of Technology and Engineering Course Credits

	College/University	Technology Credits	Engineering Credits	Housed In
1	Central Connecticut University	24	9	Engineering
2	Colorado State University	0	42	Engineering
3	Eastern Kentucky University	30	3	Non-Engineering
4	Indiana State University	27	0	Non-Engineering
5	North Carolina State University	31	0	Non-Engineering
6	Purdue University	27	3	Non-Engineering
7	The College of New Jersey	9	27	Engineering
8	Utah State University	9	20	Engineering
9	Appalachian State University	19	0	Non-Engineering
10	Ball State University	21	3	Non-Engineering
11	Bowling Green State University	12	12	Engineering
12	Buffalo State College	27	0	Engineering
13	California University of Pennsylvania	27	12	Engineering
14	Pittsburg State University	29	0	Non-Engineering
15	Rhode Island College	27	0	Non-Engineering
16	St. Cloud State University	24	3	Engineering
17	State University of New York (Oswego)	39	0	Non-Engineering
18	University of Arkansas	24	5	Non-Engineering
19	University of Central Missouri	16	6	Non-Engineering

The data were entered into a statistical software package, SPSS 17, and coded to reflect where the program is housed and the use of engineering in the title. The data were evaluated for normality of distribution and determined to be in violation. Therefore, non-parametric statistics were used in analyzing the data. A Mann-Whitney test was performed to find differences in engineering content between the groups of programs with engineering in the title and those without engineering in the title. A Mann-Whitney test was also done to find differences in engineering content based on whether the program was housed in a college of engineering versus a college of education. In addition, effect sizes were calculated using Cohen's *r* (Cohen, 1988). Effect sizes provide a standardized method for comparing results to determine the strength of relationship between variables (Field, 2005). An effect size of 0 means there was no effect from the engineering exposure, and an effect size of 0.8 corresponds to a large effect from the exposure (Morgan, Leach, Gloeckner, & Barrett, 2007). Cohen's *r* was calculated by dividing the *z*-score by the square-root of the sample size, N (Field, 2005). A two-way or factorial ANOVA was also done to explore interactions between the two independent variables, engineering in the title and where the program is housed.

Findings

To compare technology education programs that have adopted the term engineering into their title with those that have not, a Mann-Whitney test comparing the engineering content was executed. As shown in Table 4, programs not having engineering in the title (Mdn = 3.0) did not statistically differ from programs with engineering in the title (Mdn = 6.0), $U = 29.0$, ns. The effect size, using Cohen's *r*, is approximately -0.29, which is a medium effect (Cohen, 1988).

Table 4

Mann-Whitney Test for Engineering Content Based on Program Title Containing Engineering

Group	Median	SD	Mean Rank	*U*	*p*	*r*
Engineering Not in Title	3.00	4.63	8.64	29.0	0.20	-0.29
Engineering in Title	6.00	15.30	11.88			

A similar analysis was done to determine any statistically significant differences between technology education programs housed in colleges of engineering and technology education programs housed in other colleges, regardless of the program title. As shown in Table 5, there was a statistically significant difference between the two groups, $U = 11.5$, $p = 0.006$. The effect size, *r*, also increased from the previous grouping to -0.63. This is considered to be a large effect (Cohen, 1988).

Table 5

Mann-Whitney Test for Engineering Content Based on Where Programs are Housed

Group	Median	SD	Mean Rank	*U*	*p*	*r*
Housed in Engineering	12.0	13.72	14.06	11.50	0.006	-0.63
Housed Elsewhere	0.00	2.27	7.05			

To gain a better understanding of how the two independent variables (engineering in the title and where the program is housed) react with each other, a two-way or factorial ANOVA was used. Table 6 (next page) shows the means and standard deviations for engineering content separately for the engineering in the title groups and where the program is housed groups. Note that due to the small sample size of the preliminary study, the segregated group of programs with engineering in the title that also resides in a college of education only has one program. As statistical significance and power are directly related to sample size, these preliminary results should be looked at cautiously and used to guide or inform a more in depth study and not to draw conclusions.

As shown in Table 7, there was not a significant interaction between engineering in the program title and where the program is housed ($p = 0.44$). There was also not a statistically significant effect of engineering in the title on engineering content, $F(1, 14) = 0.08$, $p = 0.78$, or where the program is housed and engineering content, $F(1, 14) = 2.11$, $p = 0.17$. However, this result could be attributed to the small sample sizes of the segregated groups.

Table 6

Means and Standard Deviations Segregated by Title and Where Housed

	Engineering Not in Title			Engineering in the Title			Total	
Housed	n	*M*	*SD*	n	*M*	*SD*	*M*	*SD*
Education	6	2.33	2.73	1	0	------	2.00	2.65
Engineering	5	5.40	6.15	6	10.33	10.84	8.09	8.97
Total	11	3.73	4.63	7	8.86	10.64	5.72	7.69

Table 7

Results of the Two-Way ANOVA

Variable and Source	*df*	MS	*F*	*p*
Eng. in Title	1	4.41	0.08	0.78
Housed	1	117.10	2.11	0.17
Eng. in Title*Housed	1	34.44	0.62	0.44
Error	14	55.42		

Conclusions and Discussion

This study was done to determine the differences in engineering content offered by technology education licensing programs. In particular, the study compared programs that acknowledged engineering content in their program by adding the term *engineering* to the program's title to programs that did not. In addition, this study looked at the differences between technology education programs housed in colleges of engineering versus programs housed in colleges of education, technology, business, fine arts, etc. It was found that programs with engineering in the title did not significantly differ in their engineering content from programs without a change in name. This could indicate that some programs have adopted the term engineering into their title without increasing the engineering content of their program. If this is the case, a technology teacher graduating from a program with engineering in the title would not be any more prepared to teach engineering content than graduates from a traditional technology education program. An alternative, and more positive, view is that technology programs are increasing engineering content without changing their name. It should be noted that the average number of engineering content credits of all the programs is only 7.63 (more than two courses). Regardless of the name or location, this amount of engineering content seems low compared to requirements to teach in other content areas.

When the groups were segregated based on where they were located within the university or college, regardless of the name, significant differences in engineering content were found. Technology education programs in colleges outside of engineering had a mean of 2.0 engineering content credits (less than one course), while technology education programs in colleges of engineering had a mean of 8.1 engineering content credits (more than two courses). This result suggests technology education programs housed in engineering colleges are more likely to incorporate engineering into their curriculum regardless of program name. This could be a factor of shared courses between engineering and technology programs or a more positive view of engineering by the technology faculty and administration. It can be assumed that technology educators graduating from technology education programs located within colleges of engineering are better prepared to teach engineering concepts than educators graduating from programs located in colleges located outside of engineering. This is independent of the name of the technology education program.

As a final analysis, this preliminary study examined the interaction of both the title of the program and where it is housed by segregating the programs with engineering in their title and those without by where they are housed. While differences in the means were large and noteworthy, statistical significance was not achieved. For example, programs with engineering in their title that were housed in colleges of engineering had a mean of 10.3 credits of engineering content (more than three courses), while programs with engineering in their title that were housed in colleges other than engineering had a mean of 0.0. Further research with a larger sample size is needed to explore the interactions between both of the independent variables identified.

The current subject matter knowledge requirements based on the Elementary and Secondary Education Act, formally known as the No Child Left Behind Act, for a Highly Qualified Teacher include either an academic major in the field that the teacher will be teaching, a graduate degree in the field, or coursework equivalent to a major (30 semester credit hours) (Dorn, 2011). Science teachers generally either have a science degree or enough credits to warrant a minor in science (15 semester credit hours). The same is true with history, English, mathematics, and other licensing subjects. Therefore, it is logical to conclude that students should have expert content knowledge of engineering concepts before teaching engineering. However, this study showed an overall average of 7.63 credits, 22.37 credits less than the 30 credit hours required by the Elementary and Secondary Education Act for teaching in other disciplines. While technology education programs have taken strides to identify with engineering through name, the required content appears to be lagging behind.

Further Research

The next step for this research study is to find more programs to add to the study and gain greater knowledge about the content covered in the programs within this study. The NCATE website lists accredited programs in each of the 50 United States. Every program needs to be evaluated and added to the model, based on whether or not the title contains the term engineering and where the program is housed. Additionally, other curriculum characteristics are going to be added to the analysis. These include course syllabi and additional course descriptions, the highest mathematics course required, number and type of science courses such as physics and chemistry, and the nature of the laboratory courses. The extent of engineering content within the technology programs can then be evaluated by comparing the programs to ABET accredited engineering programs.

The researchers acknowledge that some engineering content may be conveyed within courses that do not have engineering in the title. As there is little research on the amount of engineering content within technology programs, this study should be used as a starting point instead of a conclusive document. Further research may include an in depth analysis of program content through artifact collection, instructor interviews, or other means to obtain an accurate description of content deemed to be engineering related.

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Are We Missing Opportunities to Encourage Interest in STEM Fields?

The disciplines of science, technology, engineering, and mathematics (STEM) have experienced problems in producing adequate numbers of graduates to meet workforce needs in these fields. Although entrance into the STEM fields has grown, this growth is not keeping pace with the overall needs of the labor market (CPST, 2007; Lowell & Regets, 2006). Since 2001, a decline in the share of total employment in STEM areas has been seen (CPST, 2007). A report by the Commission on Professionals in Science and Technology (CPST, 2007) notes that, while our nation's workforce is growing in these fields, it still lags behind the overall growth of the United States, resulting in a serious deficit in the supply side of the STEM workforce. From 2001 to 2006, STEM employed professionals declined from 5.6% to 5% in the United States. This decline mirrored post-secondary enrollment in STEM degree fields (Ashby, 2006). While the actual enrollment in STEM degree fields increased from 519,000 students in 1994-1995 to 578,000 students in 2003-2004, the proportion of undergraduate degrees awarded in STEM fields actually declined from 32% to 27 % of all degrees awarded. This decline has significant economic implications, since the United States needs to produce more graduates in the STEM fields to maintain its competitiveness in technological areas (COSSA, 2008).

Better understanding of the important influences in career considerations is crucial to help guide interventions aimed at improving career access in the STEM fields. As noted by the CPST report (2007), we are at a critical position in regard to the future workforce in STEM areas, and we need to address why these fields are not attracting future professionals and the influence this may have on the long-term global competitiveness of our nation. Reports indicate that, on average, there are 200,000 vacant engineering positions annually in the United States (Machi, 2008). Machi (2008) notes that the United States is graduating roughly 60,000 engineer students annually in comparison to China and India, where both countries produce approximately 600,000 annually. The United States is currently ranked 20th in the world in the proportion of students earning a four-year degree in engineering or natural science (Kuenzi, 2008). Students in the United States are far less likely to earn a four-year degree in engineering or science than students in other countries (AAU, 2006).

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Numerous studies have been conducted on factors influencing students' choice of major (Beggs, Bantham, & Taylor, 2008; DeMarie & Aloise-Young, 2003; House, 2000; Kuechler, McLeod, & Simkin, 2009; Malgwi, Howe, & Bunaby, 2005; Schwartz, 2004; Tan & Laswad, 2009). Studies have identified personal interest as a key factor (Beggs et al., 2009; Kuechler et al., 2009). In a survey of 852 college students, Beggs et al. (2009) identified various factors influential in choice of major with interest in a field being rated as the most important influence. Other contributing influences cited by college students were parents, friends, relatives, professors/teachers, and counselors. Job characteristics were also influential and included factors such as beginning salary, earning potential, benefits, and advancement. Other areas included factors related to the major/degree such as ease in earning degree, faculty reputation, and introductory course. The researchers noted that, while the student's own interest was the highest rated influence in considering a major, this required having knowledge of that area. If a student has never been exposed to a particular area, then interest cannot develop.

If we are not attracting sufficient numbers of students into STEM careers, what factors might be influencing consideration of these fields? The purpose of the study was to ascertain what factors were influential in developing an interest in career options among high school students. The study further sought to determine the knowledge of school personnel and parents about STEM careers, since they are often cited as key influences in students' choice of major (Malgwi et al., 2005). Last, the study sought input from current college students completing an engineering program on when they had made a decision to pursue their current major and the factors that influenced their choice. Our central research questions were: (1) How did high school students rate various factors in influencing their interest in career options? (2) Given past research citing the influence of parents and school personnel on students' consideration of a field of study, what knowledge of STEM fields did these individuals have? (3) Were the influences reported by high school students similar to the reported influences of college students majoring in engineering? and (4) When did college engineering students report deciding on a major? Through this study we hoped to provide a more integrative summary of factors influencing the choice of STEM fields, engineering in particular.

Methods

High School Participants

One hundred thirty-two high school students—ranging in age from 12 to 18 (mean age of 14.6) and ranging in grade from freshman to senior (61 students for summer of 2007 and 71 students for summer of 2008)—were extended invitations to attend the Information Technology Academy for Students (ITAS). Seven students were unable to attend after accepting the invitation, and six students left before the end of the three-week ITAS academy. One hundred nineteen students were in actual attendance for the entire three weeks of the academy. One male student failed to complete the survey leaving a data set of 118 students—63 (53.4%) female students and 55 (46.6%) male students. The race/ethnicity of the students was as follows: American Indian 2 (1.7%), African American 52 (43.7%), Pacific Islander 1 (0.6%), Asian 2 (1.7%), Hispanic/Latino 15 (12.6%), Caucasian 42 (35.3%), and other 5 (4.2%). Three of the students were rising eighth graders, 16 students were rising high school freshmen, 61 sophomores, 31 juniors, and 8 seniors.

High School Student Survey

A two-part questionnaire was used to ascertain the influence of various factors in students' consideration of career options. Part A of the questionnaire focused on specific influences on career choices and the student's interest in career options. This part asked students to rate 10 specific influences on their career considerations using a five-point Likert scale from 1 (*no influence*) to 5 (*very strong influence*). The areas of influence included factors such as friends, peers, parents, teachers, counselors, the media, degree options, earning potential, and affordability of college program. The second part of the questionnaire (Part B) asked students to rate how important five factors were in developing their current career interests from 1 (*not important*) to 5 (*very important*). This section included factors such as having friends with same interest, someone in their family who was working in a particular field, having a teacher who encouraged them about a field, and having someone at their school that was knowledgeable about different career options. The questionnaire for the current study was based in large part on a previous NSF project (Gross, 1988) that identified key factors in encouraging students in mathematics (i.e., good teachers, school personnel, negative teachers, peers, home environment). Research by Malgwi et al. (2005) that cited student interest, earning potential, peers, parents, and school as influential in encouraging students to consider a career field, also significantly influenced the development of the current questionnaire.

Parent Participants

Parents of potential academy students were asked to complete a brief, anonymous survey regarding their aspirations for their sons/daughters. One hundred eighty-four parents completed the surveys. The majority of respondents were mothers (67.9%), followed by fathers (21.7%), other relative (i.e., grandparent, aunt, uncle; 6%), foster parent or guardian (2.7%), and both parents completed (1.1%). Of the responding parents, 43.5% were African-American, 42.4% Caucasian, 1.6% Native American, 0.5% Asian, and 12% Hispanic or Latino. Fifty-two percent indicated they were the parent of a daughter, and 48% indicated they were the parent of a son. Regarding grade level, 66.1% indicated their son/daughter was a freshman in high school, 23.9%

sophomore, 5.6% junior, and 3.9% senior. Approximately 90% of parents/guardians indicated they had graduated from high school, with 66% indicating they had received some post-secondary training.

Parent Survey and Procedure

Symposiums were held for the parents of potential academy students at each of the participating school districts/high schools in the spring of 2007 and 2008. Not all parents of potential academy students were in attendance, and some parents attended whose son/daughter did not attend the academy. The focus of the symposiums was to make parents aware of the academy, the selection process, the potential benefits for their sons/daughters, and address any concerns they might have in allowing their sons and daughters to attend a residential program on a college campus.

In addition to demographic questions (i.e., race/ethnicity, relationship to parent/guardian's highest level of education), parents were asked how far they wanted their son/daughter to go in school and how often they talked with their son/daughter about courses, grades, plans post-high school, jobs/careers, college entrance exams, and application to college. They were also asked how much they knew about college/university admission procedures; financial aid for college; careers in different fields; and specifically knowledge of careers in science, math, engineering, and technology.

High School Personnel Participants

Thirteen high school math teachers, 12 science teachers, and 8 school counselors (12 men and 21 women) completed a survey regarding their knowledge about careers in the STEM fields in January of 2007 to aid in developing information for the NSF grant. Math and science teachers in five rural school systems were asked by their school administration to participate. Forty-two surveys were sent to teachers at the schools agreeing to participate in the summer academy, and 33 completed surveys were returned. The average time in the teaching profession of those completing the survey was nine years (range 1 to 27 years). One of the goals for our grant was to make STEM careers more of an option for consideration by rural high school students. In order to assess where efforts might be most beneficial in regard to the grant, this part of the study was conducted to better understand the current knowledge of and encouragement by school personnel about the STEM fields at the high school level. Three different concentrations (math, science, and school counselors) were chosen to match the identified groups that the grant would be working with during the academy.

High School Personnel Survey

Teachers were asked to rate on a four-point Likert scale—ranging from 1 (*strongly disagree*) to 4 (*strongly agree*)—their knowledge about careers in scientific fields in general and, specifically, their knowledge about careers in information technology (IT) and engineering (i.e., "I feel that I am very knowledgeable about careers in ___").

College Student Participants

Eighty-three students enrolled in an introductory course for engineering majors, and 24 seniors who were scheduled to graduate at the end of spring semester 2008 (this represented the first graduating class for a recently implemented engineering program) were surveyed. Of the 83 students beginning the program, 72 were male and 11 were female with a mean age of 21.03 (range 18-37 years). Seven students were African American, 2 Asian, 2 Hispanic/Latino, 69 Caucasian, and 3 designated biracial. Of the 24 seniors, 21 were male and 3 were female with a mean age of 22.42 (range 21-30 years). One student was African American, 21 were Caucasian, and 2 indicated biracial.

College Student Survey

The survey was the same as administered to the high school students with the addition of one question: "When did you decide on engineering as your career choice?" The decision to participate or not participate was voluntary, and there was no penalty for choosing not to participate. Given the low retention rate in some of the STEM fields (House, 2000; Morton, 2007; Tsui, 2007), it was felt that surveying both entering and exiting students would provide more valid information, as well as possibly pinpointing any difference between those who were retained and those who were not.

Research Protocol

The research protocols were approved by the university's Institutional Review Board (IRB) and conformed to American Psychological Association (APA) ethical guidelines for research with human participants. The decision to participate was voluntary for all participants, and there were no penalties if anyone chose not to participate. In order to obtain consent with high school students, parents completed a consent form for their son/daughter to participate in the study, and the son/daughter completed an assent form as a minor as well. Both forms were required for the high school student's responses to be included in the study.

Results

High School Students

For Part A of the survey, high school students rated their interest in a field as the most important consideration in a career choice with their parents' influence as second. Third was the earning potential, and fourth in their ratings was the influence of a teacher (see Table 1). When next asked about the importance of various factors in the interests they have (Part B), the key influence was the knowledge of school personnel about various fields, followed by having a teacher encourage a particular field. While students rated other factors relatively high, these were the primary areas noted as most influential in encouraging them to explore career options.

Table 1
Means and Standard Deviations for High School Students and College Students Reports of Career Influence (n = 225)

	High School Students (n = 118)	Freshmen College Students (n = 83)	Senior College Students (n = 24)
Part A: How much do you feel each of following influences your thinking about future career options?			
Friends	3.08 (1.21)	2.62 (1.09)	2.63 (1.01)
Parents	**4.21 (**1.05)	**3.79** (1.06)	**3.71** (1.23)
Teacher	**3.99 (**1.00)	**3.40** (1.12)	**3.38** (1.17)
Negative Influence of Teacher	1.96 (1.06)	2.00 (0.99)	1.35 (0.57)
Cost of Degree	3.50 (1.28)	2.88 (1.28)	2.43 (1.50)
Time to Degree	3.17 (1.26)	2.84 (1.21)	2.13 (0.92)
Earning Potential	**4.11** (1.04)	**4.08** (0.81)	**4.00** (0.72)
Interest in area	**4.62 (**0.74)	**4.44** (0.77)	**4.65** (0.57)
Stay in Region	2.46 (1.32)	2.28 (1.34)	2.43 (1.38)
Media	2.72 (1.22)	2.62 (1.16)	2.13 (0.92)
Part B: How important are the following to the career interests you currently have?			
Friend with Same Interest	3.43 (1.13)	**3.32** (1.06)	**3.63** (0.82)
Interest as Same (Gender) Friend	3.01 (1.11)	2.95 (1.09)	3.08 (1.10)
Occupation of Family Member in Field	3.05 (1.21)	2.59 (1.29)	2.25 (0.99)
Teacher Encouraging Field	**3.85 (**1.08)	2.81 (1.15)	3.25 (0.79)
Knowledge of School Personnel about Career Field	**4.10** (1.06)	**3.40** (1.17)	**3.67** (1.24)

Parent Survey

All the parents surveyed indicated that they wanted their son/daughter to obtain an education beyond the high school level. Of those parents responding to this question (181 out of 184), one parent indicated a vocational or technical school (0.6%), 39 (21.5%) indicated a four-year college degree, 37 (20.4%) indicated a master's degree of equivalent, and 104 (57.5%) indicated a PhD, MD or other advanced degree. All had hopes that their child would pursue a degree beyond high school with the majority (77.9%) indicating they wanted their child to go beyond a four-year college degree. Certainly these parents are aware of the advantages of higher education and have high aspirations for their son/daughters.

The parents were then asked how frequently they interacted with their adolescent regarding school and future careers by responding to a series of questions based on a four-point scale ranging from 1 (*never*) to 4 (*5 or more times in past few months*). The responses are presented in Table 2. Parents reported valuing education and actively encouraging their son/daughter in school areas. While they also reported involvement in talking with their adolescents regarding preparing for college and applying to college, these two areas reflected relatively lower ratings possibly due to being less knowledgeable about these particular areas.

Table 2
Percent of Parent Responses Regarding Talking with their Adolescents about School and Careers (n = 184)

	1	2	3	4
Selecting school courses	0.6	11.0	35.4	53.0
Discussion about grades	--	1.6	12.6	85.7
What your son/daughter will do after high school	0.5	3.3	15.4	80.8
Discussion of jobs/careers	--	6.0	16.9	77.0
Discussion about preparing for college (i.e., entrance exam such as SAT)	4.9	13.7	30.2	51.1
Discussion about applying to college	0.5	12.6	25.1	61.7

(1 = *never*, 2 = *1-2 times*, 3 = *3-4 times*, 4 = *5+ times*)

The last series of questions asked parents to rate their knowledge about higher education processes, as well as their knowledge about jobs and careers, on a five-point scale ranging from 1 (*very little*) to 5 (*a great deal*). Results are presented in Table 3 (next page). As seen below, there are some areas where parents felt their knowledge was limited. In particular, the parents' ratings of their knowledge about science, math, engineering, and technology programs were weak in comparison to other areas they rated.

Table 3
Parental Knowledge about College and Career Topics

	1	2	3	4	5
Information about colleges	12.1	13.7	35.7	22.0	16.5
The college admissions process	14.8	19.2	28.0	19.8	18.1
Financial aid for college students	15.9	20.9	28.6	18.1	16.5
Jobs/careers in different fields	11.5	15.9	37.4	19.8	15.4
Information about science, math, engineering, or technology fields	25.6	27.8	32.8	6.7	7.2

(*1 'very little' to 5 'a great deal'*)

High School Teachers

Three areas emerged as concerns in regard to STEM fields from the surveys of 33 high school math (11) and science (12) teachers and counselors (10): 32.3% did not feel that they were knowledgeable about career options in scientific fields; 62.5% did not feel that they were knowledgeable about career options in information technology; and 61.3% did not feel that they were knowledgeable about engineering career options. Means and standard deviations for each of the three questions are presented in Table 4. Math teachers rated themselves slightly higher than science teachers or counselors in knowledge of careers in scientific fields, but all groups were consistently low in knowledge of careers in information technology and engineering.

Table 4
Means and Standard Deviations of Teachers' Knowledge of Careers in Fields of Science, Information Technology and Engineering

Source	Scientific Fields	Information Technology	Engineering
Math Teachers	3.15 (0.69)	2.23 (0.83)	2.23 (0.73)
Science Teachers	2.55 (0.69)	2.42 (0.79)	2.54 (0.69)
Counselors	2.84 (0.69)	2.34 (0.75)	2.36 (0.66)

1 (low) to 4 (high)

College Students

College students (both introductory and senior college students in engineering) completed the same questionnaire administered to high school students. Part A of the questionnaire asked what influenced them to think about a career in engineering, and their ratings closely mirrored those of the high school students (see Table 1). Interest in the field was rated the highest by both introductory and senior students, followed by earning potential, then parents, and high school teacher. Both high school students and college students were consistent in the top four rated influences, but the second and third highest rated influences were reversed for the two groups.

Part B of the questionnaire asked college students what factors influenced their interest in different careers. The highest rated influence was the knowledge of school personnel about career options, followed by having a friend with the same interest. One of the strongest reported influences was the same as it was for high school students, having someone in the school system that had knowledge of career options.

This study also asked the university students in engineering when they had decided upon engineering as a major, and 34.7% of the students in an introductory engineering course indicated after entering college, 55.1% indicated in high school, and 10.2% before high school. For the college seniors, 50.2% indicated the choice was made in college, 45.8% indicated the choice had been made in high school, and 4.2% reported earlier than high school. For both of these college groups, close to half reported that the decision to consider a major was made in high school.

Discussion

This study focused on the assessment of student influences on career choices and the knowledge of STEM career fields of students, parents, and teachers. The top four influences on career choice reported by students were personal interest, parents, earning potential, and teachers in that order. These results are consistent with other studies that have indicated student interest, parents, and teachers played significant roles in the development of career interests by students (Gross, 1988; Malgwi et al., 2005). While parents and teachers represented strong influences on consideration of potential careers, their knowledge of STEM occupations was found to be limited. This has the potential to seriously reduce students' consideration of STEM fields, especially in information technology and engineering. A catch twenty-two situation existed in that, while personal interest, parents, and teachers were rated as the top influences, students need to have knowledge about careers to ascertain if they are personally interested in a field. Without the support and encouragement of parents and teachers to explore options in STEM fields, many students may never even consider these fields.

Not all students enter college with a declared major and many students also change majors (Donnelly & Borland, 2002; Ohland et al., 2008). Ohland et al. (2008) reviewed extensive databases with information on over 300,000 first time students, covering nine institutions of higher learning. They found that 23% of these first time students entered college without a declared major. While many disciplines benefit from matriculation of this group, STEM fields, engineering in particular, do not, with less than 3% of these undeclared students matriculating into STEM fields. Ohland et al. (2008) go on to note that 93% of students enrolled in engineering after eight semesters also entered college with this same major, with other majors ranging from 35%-59%. While engineering had a high persistence rate compared to other fields (57%), they were not attracting undeclared or change of major students. In comparison, over 40% of students majoring in computer science and other STM fields came from other majors. These findings strongly suggested introduction to these fields at the secondary school level is paramount if students are to be encouraged to pursue STEM fields, especially engineering.

It was also found that the responses of college students in engineering programs closely mirrored the same influences as reported by the high school students, with school personnel and teachers being cited as having a strong influence on their decision of major. There has recently been a greater emphasis on developing a STEM presence at the high school level through collaborative partnerships with the potential for building interest in and attracting students to STEM fields (Merrill, Custer, Daugherty, Westrick, & Zeng, 2010). The secondary school setting represents a critical point in helping adolescents become aware of potential STEM careers and connecting these career decisions to educational decisions.

Two primary influences on student decision-making, parents and school personnel, were found to have limited knowledge of STEM careers, especially in regard to information technology and engineering. Prior research indicates that parental influence is especially important to adolescents during the high school years in career considerations, and that adolescents do value their parents' input (Keller & Whiston, 2008; Lucas, 1997; O'Brien, Friedman, Tipton, & Linn, 2000). As noted by Keller and Whiston (2008), it is not necessarily explicit information (i.e., mechanical vs. biomedical vs. aerospace vs. mechanical engineering) that parents need but basic information to foster and support their adolescents' exploration of careers.

Of special concern from the current study is the limited knowledge of science and math teachers and counselors with respect to STEM careers, especially information technology and engineering. There is a need to meaningfully engage students in science, technology, engineering, and mathematics if the United States is to compete and lead in the 21st century. One barrier is the lack of well qualified teachers in these fields (Congressional Research Service, 2006; Paldy, 2005). Students' lack of interest in scientific careers may reflect the shortage of qualified teachers and poor facilities in many schools (Paldy, 2005). Finding effective ways to attract and retain well-qualified teachers in STEM fields is critical (Steinke & Putnam, 2007). Further, if teachers are not adequately prepared, they may use ineffective methods and techniques to teach dynamic subjects (Christie, 2008; Ritz, 2009; Wicklein, Smith, & Kim, 2009). How, when, and by whom students are offered opportunities to explore technology in secondary schools is an ongoing issue (Wicklein et al., 2009; Wright, Washer, Watkins, & Scott, 2008).

Counselors also hold key roles in encouraging students to consider career options. However, Smith (2009) notes that less than ten percent of school career advisors come from a science background and do not have the information or expertise to adequately guide students into STEM opportunities. The lack of knowledge/expertise on the part of counselors in regard to STEM careers, coupled with limited expertise on the part of teachers, presents major problems in ensuring students are made aware of STEM career opportunities.

The lack of STEM education, opportunities, and career guidance is not only at the general educational level, but specifically a problem with underserved and underrepresented populations (Gilmer, 2007; Lam, Srivatsan, Doverspike, Vesalo, & Mawasha, 2005; Yelamarthi & Mawasha, 2008). Support through the educational system is especially important in encouraging young women and minorities (Kauffmann, Hall, Bosse, Batts, & Moses, 2009; Sullivan, Hall, Kauffmann, Batts, & Long, 2008). There has also been much debate concerning the commitment of higher education leaders to the achievement of diverse individuals in STEM careers (Hopewell, McNeely, Kuiler, & Hahm, 2009). Students, teachers, and leaders must understand that STEM fields are not only a pathway for understanding the world, but are also connected to social standing, economic prosperity, and healthier living. It is critical that people of diverse and underrepresented backgrounds get education, exposure, and career guidance in order to bridge the “STEM divide” which exists in relation and correlation to the well publicized digital divides within our society.

The results of the current study should be interpreted in light of certain limitations. The participant pool of high school students, parents, and teachers came from rural schools in the southeast, which may limit generalizability. The study, and grant, focused on high school students who had the ability to do well in the STEM fields, as indicated by their school records and teacher reports, but who may not have had opportunities to explore these fields due to limited school facilities, socioeconomic status, gender, and/or minority status. However, it should be noted that these underrepresented groups might well denote some of the best untapped resources across the US. We must attract far more students into these fields if we want to remain competitive in the world market.

Future research needs to focus on more rigorous experimental procedures in ascertaining the influence of parents and teachers on students’ career considerations. In the current study, it was not possible to match parental response to the response from a high school student. It would be beneficial to assess parent and teacher knowledge and tie this directly to the interests/career options specific students indicate.

Given the findings of this study, STEM education programs and funding sources should consider more definite connections to secondary school career counseling and parental STEM education programs. Results of the current study found that roughly half of college students in engineering made that decision while still in high school, making this a critical time period. Teachers/counselors are individuals with whom students discuss their future plans and seek counsel. If school personnel have limited knowledge of these career options, many students may not know about or consider certain careers as viable choices.

Teachers are key players in encouraging student interest in various career options (Jackson & Nutini, 2002; Kenny, Blustein, Chaves, Grossman, & Gallagher, 2003; Lent et al., 2002; Paldy, 2005). Kenny et al. (2003) and Lent et al. (2002) further note that the importance of a career support system in the educational sector in mediating negative effects of barriers.

Additionally, parent groups should focus attention on helping parents understand their role in encouraging their sons/daughters to consider various career options. It is important that parents be given broad knowledge of career options. Parental attitudes play an important role in encouraging students to consider various career options, including career exploration, gender-typing, and future occupational plans (Turner & Lapan, 2005; Turner, Steward, & Lapan, 2004; Usinger, 2005).

Unless opportunities are provided to stimulate interest and encourage exploration of career options in STEM fields, engineering in particular, we will continue to have fewer students even consider these careers as options. As noted by Ritz (2009) exposure to educational experiences that promote analytical problem solving is beneficial to all students.

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Experts vs. Novices: Differences in How Mental Representations are Used in Engineering Design

Mental representation is an important cognitive construct when solving engineering design problems. When students are given a design problem, they must decide what is known, the constraints they have to work with, and what is required by the customer. They then use mental representations, such as metaphors, analogies, and propositions, to make sense of the problem and develop a solution.

Several studies have investigated the use of mental representations in problem solving. For example, Greca and Moreira (1997) investigated the use of mental models, propositions, and images by college students in solving physics problems involving electrical and magnetic fields. Their findings suggested that students work mostly with propositions unrelated to, or interpreted according to, mental models. Gick and Holyoak (1980) investigated the provision of source analogs prior to the tackling of a problem that is superficially different, but conceptually similar. Casakin and Goldschmidt (1999) examined the use of visual analogs by expert and novice designers in their work. The results of both studies indicated that people are good at utilizing prior problem and solution information when they are directed to do so, but then may not be efficient in detecting analogous information under unprompted conditions. Other studies (Holyoak & Koh, 1987; Keane, 1987) show that past analogies are more readily activated when there are surface similarities in the target problem and the analogy.

Conceptual Framework Guiding the Study

There are several types of mental representation, but for the purpose of this study propositions, metaphors, and analogies were investigated. A proposition refers to the smallest unit of knowledge that one can sensibly judge as true or false. According to Paivio (1990), propositions are the most versatile of representational concepts because they can be used to describe any type of information. They are strings of symbols that correspond to natural language. Unlike language, however, propositional representations are assumed to be "completely amodal, abstract, conceptual structures that represent information in the same way regardless of whether the information is experienced verbally, as a spoken or written sentence in whatever language, or nonverbally, as a perceptual scene" (Paivio, 1990, p. 31). The relevance of propositions for engineering

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design lies in the fact that they can be expressed as general principles, rules of thumb, or heuristics; as specific physical laws, such as those used in physics; or as mathematical formulas (Greca & Moreira, 1997). Mathematical formulas, scientific principles, and heuristics are important tools that engineers use when performing design activities (Eide, Jenison, Mashaw, & Northrup, 2002).

Metaphors and analogies are important representations used by designers in design problem solving (Casakin & Goldsmith, 1999; Daugherty & Mentzer, 2008; Hey, Linsey, Agogino, &Wood, 2008). Metaphorical reasoning allows one to make conceptual leaps across domains from a source to a target, such that a new situation can be characterized and understood by reference to a similar one. In respect to designing, metaphors are often used in the early stages of the design process to help the designer frame the problem. Besides being used descriptively to define the problem and understand the situation, they can also be used prescriptively as a solution generation tool.

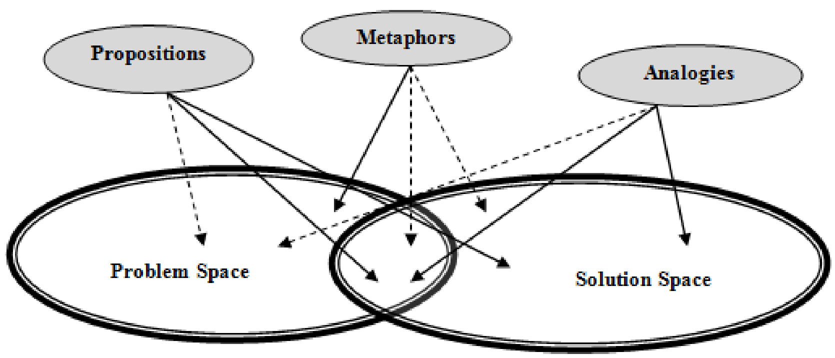
An analogy can be defined as the "illustration of an idea by means of another idea that is similar or parallel to it in some significant features" (Hey et al., 2008, p. 283). Analogies make the solution of a problem in the target domain possible by superimposing upon it a solution from the base domain (Lewis, 2008). In contrast to metaphors, analogies tend to be used more during the generation of solutions and ideation phase of design, rather than during the framing phase to assist in understanding the problem. Analogies are generally used to solve functional issues. Analogies can be categorized as between-domain (large distance) and within-domain (local). Large distance or between-domain analogies exist when there are little surface similarities between the source and target, while local or within-domain analogies exist when there are greater superficial similarities between source and target (Christensen & Schunn, 2007). An example of a between-domain analogy is trying to develop a door handle for the auto industry and comparing the door handle with a telephone or an oyster. A within-domain or local analogy is comparing the door handle to various car door handle designs. Designers use analogies to support concept selection. Analogies also assist the designer in predicting the performance of design concepts (Hey et al., 2008).

Table 1
Example of Proposition, Analogy, and Metaphor

Mental Representations	Examples
Propositions	Mathematical and engineering science formula and rule of thumb. Example of Formula: $F = mv^2 / r$. Example of Heuristic: lowering the fame will lower the center of mass.
Analogy	Comparing an idea with another idea that is similar in structural and relational features, e.g.,comparing the surface texture of a leaf with the surface texture of a plate in a battery. **Within-Domain Analogies**—analogies that are from the same domain, e.g., comparing two types of scissors; comparing two types of bicycles. **Between-Domain Analogies**—analogies drawn between two ideas from different domains but are used to resolve functional issues in a design, e.g., comparing the shape of car to the shape of a fish for aerodynamic reasons; comparing a device to remove blood clots to a plumbing or piping system (Hey et al., 2008).
Metaphor	Allows one to make conceptual leap across domains from a source to a target so that a new situation can be characterized and understood by reference to a familiar one. They help to provide meaning to a design situation, e.g., viewing a gas station design problem as an oasis; understanding a design situation by comparing an electronic book delivery design to a restaurant metaphor (Hey et al., 2008).

The framework for this study was conceptualized by integrating the model for creative design, which illustrates the co-evolution of the problem and solution spaces during engineering design problem solving (see Dorst & Cross, 2001; Maher, Poon, & Boulanger, 1996), with mental representations, such as proposition, metaphor, and analogy. Whenever engineers are solving design problems, their problem and solution spaces co-evolve with an interchange of information between the two mental spaces. As solutions are conceptualized, the designer will check and verify information relating to constraints, specific data about the problem context, specification, cost, and so forth in the problem space. This verification often results in the emergence of a new or parallel solution space. The interchange of information between the problem and solution spaces is illustrated by the overlap of the two ellipses in Figure 1(next page).

Figure 1
Conceptual model depicting the relationship between mental representations, metacognitive regulation, and the problem and solution spaces



Note: dashed arrow = more presence; solid arrow = less presence

The problem space includes design activities, such as defining the problem, searching for information, identifying constraints, and specifying evaluation criteria. Metaphors are more likely to be generated within the problem space because they are often used descriptively in the early stages of the design process to frame the problem and better understand the design situation (Hey et al., 2008). Because the designer is trying to understand the problem, it is expected that fewer propositions (mathematics and engineering science principles) and analogies are used by the designer in the problem space.

After a number of possible solutions are generated, then the best of these solutions must be selected for further analysis. During the analysis phase, potential solutions that are not suitable may be discarded or, under certain conditions, retained with a redefinition of the problem and a change in the constraints and criteria (Eide, Jenison, Mashaw, & Northup, 2002). Analysis primarily involves the use of heuristics, mathematical formulas, and principles of engineering science—all of which are propositional in nature—to achieve proper functionality of the component or system. During this process, references are continually made to the criteria and constraints that are stipulated in the problem. This is illustrated by the overlap of the two ellipses in Figure 1. It is also expected that analogies and propositions have more presence in this overlapping space.

As the designer approaches a solution, more judgmental decisions are made about the merit of the solution. It is expected that analogy and proposition are the predominant representations within the solution space, since they are used primarily to resolve and refine functional issues of the design (Hey et al., 2008).

In a review of various types of design expertise, Cross (2004) provided a comprehensive body of empirical information describing the characteristics of expert mechanical engineers, industrial engineers, and architects when solving design problems. Some of these are:

- Expert designers select features of the problem space to which they chose to attend (naming) and identify areas of the solution space that they chose to explore (framing). In addition, expert architects' approach to problem solving was characterized by strong paradigms or guiding themes, while novices had weaker guiding themes.
- Expert designers and advance student designers exhibited fixation to their principal solution concept for as long as possible, making "patches" or slight modifications rather than discarding for alternatives.
- Whenever the cognitive cost for following a particular strategy becomes too high, expert designers will abandon or deviate from a principled, structured approach.
- Expert designers use non-linear strategies in problem solving. Often an interleaving of problem specification with solution development, drifting through partial solution development, and jumping into exploring suddenly recognized partial solution. They also use a mixture of breadth-first and depth-first approaches. Novices tend to follow a more linear depth-first approach.
- Unlike novices, experts have the ability to alternate rapidly between activity modes (examine-drawing-thinking) in rapid succession to make novel decisions.
- Outstanding designers seem to have the ability to work along parallel lines of thought. This means they maintain openness, even ambiguity about features and aspects of the design at different levels of detail, and consider these levels simultaneously as the design proceeds.
- Outstanding designers rely implicitly, or explicitly, on first principles in origination and development of concepts.
- Experts' creative solutions arise when there is a conflict to be resolved between the expert's own high level problem goal (their personal commitment) and the established criteria for acceptable solution by a client or other requirements.
- The superior performance of experts is domain specific and does not transfer across domains (Cross, 2004).

Purpose of the Study

This study investigated the mental representations of student and professional engineers while they solved an engineering design problem. The intent was to gain a deeper insight into the differences that exist in the cognitive processes of engineering students and professional engineers as they use mental representations (i.e., propositions, metaphors, and analogies) to solve the engineering design problem. The following research questions guided the study:

1. How does the frequency of propositions, metaphors, and analogies used by engineering students and professional engineers differ in the problem and solution space?
2. How do the attributes of the propositions, metaphors, and analogies used by engineering students and professional engineers differ when they are solving a design problem?

Method

A comparative case study of engineering students and practicing engineers was conducted. A purposeful, maximum variation sampling process was used (Gall, Gall, & Borg 2007). Maximum variation sampling, a special type of purposeful sampling, entails the “selecting of cases that illustrate the range of variation in the phenomena to be studied” (Gall et al., 2007, p. 182).

Sample Selection

Purposeful samples of mechanical engineering students and professional engineers from the Midwestern United States were selected. The student participants were three juniors and three seniors who had completed one or more courses with enginering design elements in their content. Each professional engineer possessed at least an undergraduate degree in mechanical engineering and had worked as an engineer for 7 to 40 years. Except for one professional engineer, their individual number of years in the profession exceeded the minimum 10 years of experience it generally takes to achieve expertise in a particular domain (Phye, 1986). A total of four professional engineers participated.

The Design Task

Each participant was given the same engineering design problem for which to find a conceptual solution. Before administration, the design task was vetted by an Engineering Technology professor with over 20 years teaching experience and a Mechanical Engineering professor with over 10 years experience as a manufacturing consultant and over 3 years experience teaching manufacturing principles. This was to ensure that the design task was sufficiently ill-structured, and of the appropriate difficulty level, to engage the students and professional engineers. The design task was then checked by a professor who teaches the senior design project course, and the task was pilot tested with a mechanical engineer with over 20 years experience (see Figure 2, next page).

Figure 2
The engineering design task

THE DESIGN TASK

The objective of this engineering design activity is to understand the cognitive process of engineering designers as they solve a design problem. Verbal Protocol Analysis will be used. This means that as you solve the problem you will be required to **"think aloud"** (say aloud) what you are thinking. If you stop speaking I will remind you to resume speaking aloud as you solve the problem. Please include all the notes and sketches of your solution on the sketch pads that are provided.

Duration: 1 hour

The Context

Fonthill is a hilly terrain in the District of St. Mary with narrow tracks and virtually non-existent roads. This area also experiences high amounts of rainfall yearly. There are several communities like Fonthill on this mountainous tropical island. Because of the very poor state of the roads the most frequent mode of transportation are motorcycles. Motorcycles are used to take residents to and from work, market, and school. While the residents see this system of transportation as essential, the government has serious concerns about the safety of the riders and their passengers. The government therefore secured a loan to purchase a fleet of motorcycles that are specially built to handle these rugged terrains. These motorcycles will be leased as taxis to specially trained riders.

The Design Problem

The Honda CRF230 is a cross between a dirt bike and a street bike. Modify the Honda CRF230 so that it is robust enough to handle repeated journeys through these mountainous terrains that are prone to a lot of rainfall annually. The average cost of a new car in this country is about US$25000.00 and the government expects that the cost of this motorcycle will not exceed one-third this cost. The motorcycle must also:

- Be equipped with more cargo carrying capacity and at the same time make the rear seating (pillion) more comfortable.
- Have an improved rack or a holding system for carrying packages, books, or a reasonable amount of groceries on the motorcycle. The rack must be non-metallic but of sufficient sturdiness to withstand a rugged terrain, occasional brushing against rocks, and a lot of rainfall.
- Be capable of enough horsepower to climb sections of mountains with slopes of 30 degrees, carrying the rider and the pillion passenger.
- Have a device to prevent the theft of helmets from the motorcycle.

Procedure

The design task was administered at a time and place convenient for each participant. Pencils, erasers, and sketchpads were provided along with the instruction for the design task. Each participant was allowed approximately one hour to complete the design solution. A $25 gift card was given to each participant.

Data was collected primarily through Verbal Protocol Analysis. The first stage of data collection, referred to as concurrent protocol, was carried out while the design problem was being solved. The second stage of data collection, referred to as retrospective protocol, was performed after the problem was solved. To prepare them for the study, each participant had the option of doing a five minute session to practice thinking aloud as they solved a simple mathematical problem. The task was administered after they were comfortable with the thinking aloud process. The participants were encouraged to speak aloud whatever they were thinking as they solved the problem. Their verbalizations were audio recorded. If the participants stopped talking, they were reminded to continue to speak aloud and say what they were thinking.

After each participant completed the engineering design problem, an interview was conducted to clarify sections of the protocol and to allow the participant to explain representations used and metacognitive strategies applied. Like the concurrent protocol, the interviews were audio recorded. Their response to the interview questions served as a supplementary data source to the concurrent protocols. A general interview guide format was used (Gall et al., 2007).

Data Analysis

After each participant completed the design task, the audio recording of the verbal protocol was transcribed. The transcribed protocols were then segmented into think-aloud utterances and coded. The problem space was primarily identified by activities, such as gathering information, defining the problem, identifying constraints, specifying evaluation criteria, and initially searching alternative solutions. The solution space was identified by activities, such as deciding between two alternatives, developing a specific solution, optimizing a selected solution, and determining specifications. The overlapping space was specifically identified in the protocol by verbatim transcription that indicated the designer was mentally transiting from the solution space to the problem space in order to gather additional information or to verify data, constraint, specification, etc., then returning to the solution, or starting a new solution. Design activities include analysis, additional information gathering, and the selection of alternative solutions.

The segmenting took place in two stages. In the first stage, larger units of analysis, called *think-aloud utterances,* were identified and segmented from each other. Think-aloud utterances comprise those words spoken aloud by a participant that were followed by some period of silence (Hartman, 1995). A total 270 utterances were segmented (150 for the professional engineers and 120 for the engineering students). Codes were assigned to each segment using nine predefined constructs—heuristic, formula, analogy, within-domain analogy, between-domain analogy, metaphor, problem space, solution space, and overlapping space.

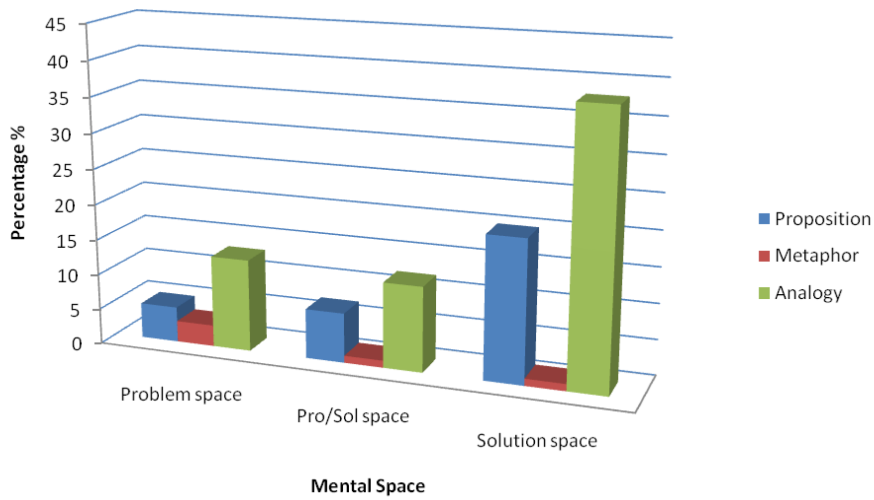
Reliability coding was conducted by having one additional person code seven pages of one transcript (Miles & Huberman, 1994). A reliability kappa coefficient of 0.76 was calculated for the first coding. All disagreements between coders were resolved through discussion. A second coding was done by both coders on the same number of pages of another transcript, and a reliability kappa coefficient of 0.9 was calculated.

Results

Frequency and Types of Mental Representations

Figure 3 (next page) illustrates that the engineering students used almost equal percentages of mental representation in their problem and overlapping spaces, 21% and 20% respectively. However, 59% of their mental representations were generated in the solution space. The professional engineers surprisingly used a very small percentage (2%) of mental representations in the problem space, 22% in the overlapping space and 76% in the solution space. The conservative use of mental representations in the problem space by the experts might be indicative of the ease with which the experts were able to understand the problem and transit into a solution mode. They then invest most of their mental representation in finding solutions.

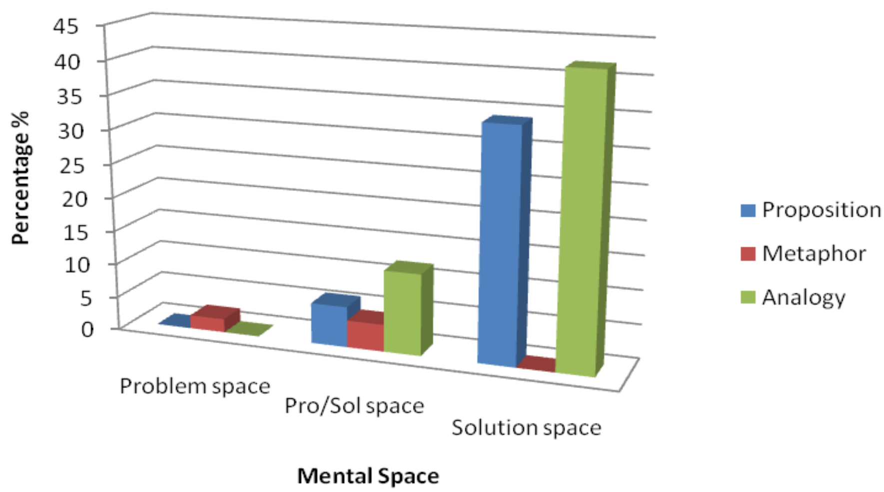
Figure 3
Frequency of proposition, analogy, and metaphor use in the problem, overlapping (pro/sol), and solution spaces of engineering students



The number of propositions used by the engineering students increased from the problem space to the solution space. Five percent was used in the problem space, 7% in the overlapping space, and 32% in the solution space. The professional engineers did not use any propositions in the problem space, 6% in the overlapping space, and 34% in the solution space. The use of propositions was less in the problem space and more in the overlapping and solution spaces for both the professional engineers and the engineering students.

The total number of metaphors used was small in comparison to other mental representations. The engineering students used a total of 4 metaphors (5%), while the professional engineers used a total of 3 metaphors (6%). Two of the metaphors used by the students were in the problem space, 1 in the overlapping space, and 1 in the solution space. In contrast, 2 of the metaphors used by the professional engineers were in the overlapping space, 1 in the problem space, and none in the solution space.

Figure 4
Frequency of proposition, analogy, and metaphor use in the problem, overlapping (pro/sol), and solution spaces of the professional engineers



The types of metaphor used were not from very distant domains and seemed to be influenced by key terms in the design question, such as "taxi," and mental images that the designers generated of the conditions in which the taxi is expected to operate. The following are examples of metaphors used. The names assigned to participants from here onward are pseudonyms:

> MAC: …*I'm struck by the difficulty of balancing large loads and a passenger on a motorcycle in this rough terrain. My initial thought was some sort of an articulated vehicle that would be attached to the rear of the motorcycle that would carry the passenger and/or luggage and provide the stability.* [Professional engineer]

> LEN: *Let's see, so I'm thinking, try to keep the design small like almost like a compact type car.* [Engineering student]

The percentage frequency of analogies used by the engineering students was 13% in the problem space, 12% in the overlapping space, and 38% in the solution space. As was the case with the use of propositions, the professional engineers did not use any analogy in their problem space. They used 12% analogy in their overlapping space and 42% in their solution space. It was also expected that analogies would be used less in their problem space and more in their overlapping and solution spaces. This proved to be true for the professional engineers and the engineering students. Overall, the engineering students surpassed the professional engineers in the percentage of analogies used (63% and 54% respectively). The percentage use of analogies by the professional engineers in their solution space exceeded those of the engineering students (42% professional engineers and 38% engineering students).

Proposition and Analogy Attributes

Figures 5 and 6 (next page) depict the type of propositions (formulas and heuristics) used by the engineering students and professional engineers respectively. Engineering students primarily used heuristics in their engineering design, while the professional engineers used heuristics and formulas more equally. Formulas and heuristics were primarily used to resolve functional issues that the designers encountered in their solution. The following are verbatim reports of occasions when the engineering students and professional engineers used propositions, such as formulas and heuristics, in their protocol.

> *VEL: "So if that's F and G this would be cosine 30 and then sine 30 or wait the other way around…Then this force would or we could use like F equals MA. Then that force minus the force in the other direction would be equal to MA. Then we could determine which acceleration we would want to calculate the force."* [Engineering student using formula]

> *LEN: "The only problem with that is it might throw off the balance of the bike but you probably just have to put more of a counter weight in the front."* [Engineering student using heuristic]

> RAY: *"If you're carrying two people and cargo, that's extra weight. You know force, mass times acceleration, and work is force times distance and then horsepower is what …W work over time. So I would look at probably, I don't think you need to go twice as big."* [Professional engineer using formula]

> MAC: *"And so my thinking there maybe I would go to two tires in the rear to provide additional heat dissipation capability, because of the smaller diameter."* [Professional engineer using heuristic]

Figure 5
Percentage of propositions used by engineering students

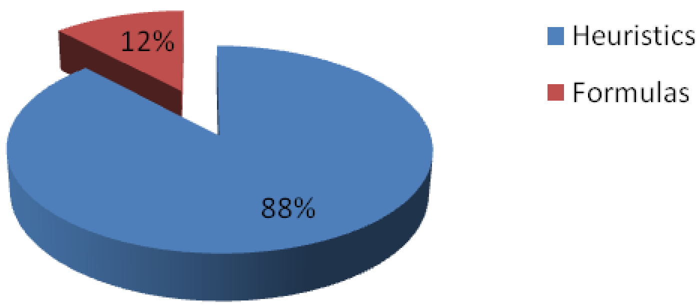
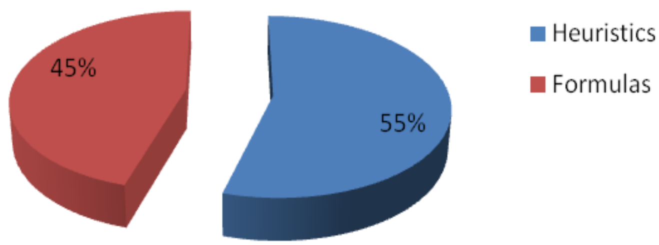


Figure 6
Percentage of propositions used by professional engineers



Figures 7 and 8 (next page) illustrate, respectively, that the engineering students used more within-domain analogies, while the professional engineers used both within-domain and between-domain analogies almost equally. A small percentage of analogies from both groups were identified as unclear because their attributes could not be identified as within-domain or between-domain.

Figure 7
Percentage analogies used by engineering students

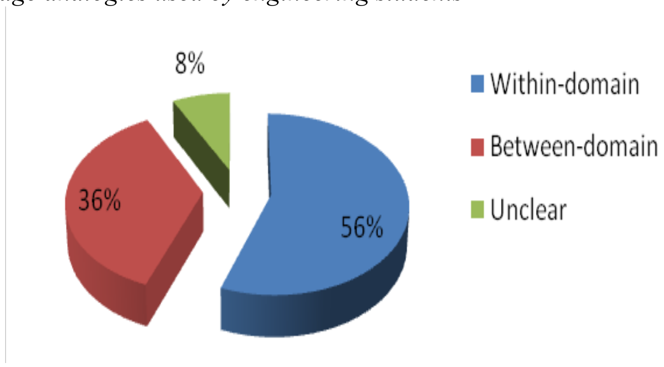
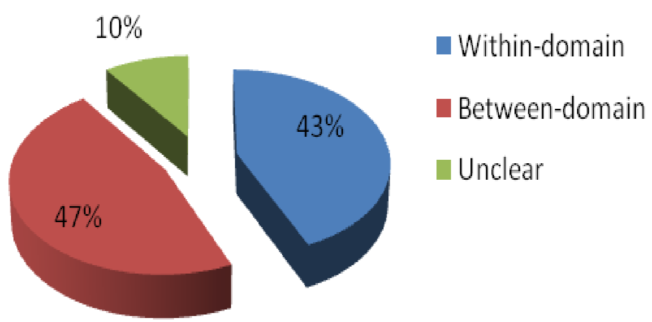


Figure 8
Percentage analogies used by professional engineers



> GUS: *"That doesn't look like it's too comfortable for the passenger so like thinking back to types of four wheelers I've ridden they always had…here is the seat so I would modify it for the motor cycle."* [Engineering student using between-domain analogy]
> LINA: *"Let's see, a device to prevent the… theft of helmets. I know a lot of motorcycles have something where in order to lift up the seat you actually have to put in your key and underneath the seat you have these little metallic…like little brackets basically."* [Engineering student using within-domain analogy]
> RAY: *"I wonder if this lock isn't automatic for the release of the helmet. Well you know cars have, you don't actually put your key in the car anymore to open up the door."* [Professional engineer using between-domain analogy]

> VEN: *"I'm trying to picture in my mind since we are talking about motorcycles and since I don't know a lot about them, I am trying to picture essentially other kinds of motorcycles and why they may be inherently stable."* [Professional engineer using within-domain analogy]

Discussion and Conclusions

The results of this study paint a picture of how four professional engineers differ from six engineering students in their use of mental representations on a conceptual engineering design task. Three major conclusions are drawn from the findings: (1) The use of mental representations, such as propositions, analogies, and metaphors, in the different mental spaces is important in engineering design; (2) Different from novices, experts rarely employed propositions or analogies in their problem space; and (3) Expert engineering designers differ from novice engineering designers on their use of within-domain analogies, between-domain analogies, heuristics, and formulas.

The type of mental representations in design varies in the problem and solution spaces of designers. In fact, within the solution space, solutions are generated by recalling forms or graphical representations and functions. In addition, ideas are evaluated by comparison with the laws of nature, capability of technology, and the requirements of the design problem itself (Ullman, 2003). The findings from the protocols indicated that the frequency of use of the various types of mental representations vary in each of these mental spaces, and the use of analogy and proposition is more prevalent, particularly within the solution space.

The greater use of analogies by the engineering students was one of the surprising findings of this study. The literature on analogical reasoning shows that analogies are important cognitive tools in design problem solving (Daugherty & Mentzer, 2008; Hey, Lensey, Agogino, & Wood, 2008; Lewis, 2008). A study by Ball, Omerald, and Morley (2004) showed that experts displayed greater evidence of analogical reasoning than did novices, irrespective of whether such analogizing is schema-driven (between-domain) or case-driven (within-domain). One explanation for this obvious disparity is the type of question and the amount of time the students spent within the problem space and the overlapping space. The retrospective protocols of both groups indicated that the participants did not have any experience in solving that type of design problem before. Except for one student who recently purchased a motorcycle and one expert who owned a motorcycle for a short time when he was younger, none were fully conversant about motorcycles. Because of the difficulty of the problem, the students spent more time planning in the problem space. They also used more analogies in both the problem space and the overlapping space. Not being acquainted with this type of engineering design problem would naturally cause the students to use more analogical representations to understand and frame the problem and to create mental models from which they generate solutions. The professional engineers' general experience and confidence, however, would cause them to immediately start exploring the solution space, accounting for the use of less propositions and analogies in the problem space and more usage in the solution space. This is consistent with earlier findings by Getzels and Csikszentmihalyi (1976) on problem finding and the creative process in art, which reported that experts differ from novices in the length of their search through the problem space, getting to the solution space faster than novices.

Christensen and Schunn's (2007) explanation of the use of the various types of analogies may offer some insight into the findings that relate to the third conclusion. They claimed that problem-identifying analogies were mainly within-domain, explanatory analogies were mainly between-domain, and problem-solving analogies were a mixture of within- and between-domain. The engineering students tended to spend more time in a problem identification mode than a problem-solving mode, possibly because of the challenging nature of the design problem, while the professional engineers were more in a problem-solving mode, as was seen by their almost equal use of both types of analogies.

There was a level of over reliance by the engineering students on the use of heuristics while the professional engineers tended to use engineering science formulas and heuristics equally. Again, the fact that this type of design problem represents uncharted territory for most of the engineering students might explain why they used heuristics or rules of thumb in search for possible solutions. According to Davidson, Deuser, and Sternberg (1995), heuristics can be used to construct mental representations when a problem solver finds that a current representation is not working. Another reason might be the cognitive cost that is involved in using heuristics. Some students found it difficult to remember certain engineering science formulas. Using heuristics, rules of thumb, or shortcuts is cognitively economical and reduces the cognitive load that students have to endure when trying to remember all the details of a formula.

Recommendations for Curriculum and Instruction

During conceptual design activities, the tasks in the curriculum that target the solution space—such as generating alternatives, analysis, optimization, and decision making—should be structured so that students are allowed to be exposed to the use of multiple forms of representations. The findings indicate that this is one way in which the experts' design cognition differed from the engineering students—in their balanced use of different mental representations. The content of curriculum and the teaching strategy used should not emphasize exclusive use of engineering science or mathematical formulas, but should also encompass heuristics and other strategies that develop students' mental models and build, not only their analytical, but also their qualitative representations. In fact, Jonassen, Strobel, and Lee's (2006) research on the everyday problem-solving strategy of engineers showed that only a small minority of workplace engineers regularly uses mathematical formulas to represent problems. They recommended that teaching in classrooms should supplement mathematical formulas with alternative qualitative representations. The objective is to build the student's repertoire of a variety of representations that would increase their ability to produce functional descriptions of design solutions, which correlate with high quality designs.

The ability to look beyond the disparate surface feature of source analogies and the design problems that they target, and identify common conceptual structures that link them together, is not easy and usually takes years of substantial experience solving different types of design problems. Gentner, Loewenstein, and Thompson (2003) opined that specific instructional intervention, such as accelerated example-based learning, may improve students' ability to solve problems in an expert-like manner. The same principle can be applied in design instruction. Instructions that expose students to a wide variety of design examples, and which allow students to make active comparisons, critiques, and evaluations to understand the underlying concepts that make certain designs similar or different, will likely result in the formation of highly structured schemas, thus improving students' ability to make analogical comparisons that go beyond surface similarities.

Recommendations for Future Research

Two recommendations are offered for future research. First, experimental studies can be conducted to show what difference exists in the quality of students' design process and products when they use any one, or a combination of the three representations—formulas, heuristics, and analogies—in engineering design. Second, verbal protocol analysis can be used to examine the use of mental representation in the problem space and solution space by working design groups of engineering students and professional engineers, as they solve a design problem over an extended period, to determine if similar results are obtained as with single participants.

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