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Moving STEM Forward

William J. F. Hunter
Illinois State University

Thank you for reading this issue of the Journal of STEM Teacher Education. Once again, we have attempted to bring you interesting and informative manuscripts that provide insight into the important work our community is conducting in integrating the STEM disciplines.

The current educational climate in the United States is fertile for our interests. The *Common Core State Standards for Mathematics* and the *Next Generation Science Standards* all speak to the practice of mathematics and science in ways that work in the real world. The mathematical practices, the science and engineering practices, and the cross-cutting concepts are significant steps toward the integration of the STEM disciplines. We applaud this movement, but we also urge you to continue to push toward greater applications in the real world and toward learning that is meaningful for students in their daily lives. I suspect that readers of this journal already believe that learning occurs more easily, more permanently, and certainly more usefully when it is grounded in students' daily lives and experiences, but I encourage you to continue to push further along that continuum.

Thank you to authors, reviewers, editors, study participants, subscribers, and funders for your support of this work. If you have any comments for the editorial team, please do not hesitate to contact us.

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An Evaluation Study of the CincySTEM ITEST Projects: Experience, Peer Support, Professional Development, and Sustainability

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Abstract

This article discusses the findings of a qualitative evaluation study of ninth and tenth grade CincySTEM ITEST projects that were designed and implemented in a new urban STEM high school. The projects were framed by project-based learning and 5E Learning Cycle principles and utilized digital backpack equipment. Many of the projects were pedagogically innovative and engaging. The study indicated that the keys to their success were teachers' accumulated experience, peer support, and professional development. The article concludes with the contributions of the study and the legacy of CincySTEM ITEST projects.

Key words: STEM education; project-based learning; urban high school STEM initiatives; digital backpacks; 5E Learning Cycle

Background

The 2008 recession amplified decades of poor academic performance among low-income students of color living in urban areas, as indicated on international assessments of achievement in science and mathematics, which are widely regarded as subjects that foster economic competitiveness (Drew, 2011). In response to this alarming trend and other educational and economic imperatives, the President's Council of Advisors on Science and Technology (2010) pushed for the "recruit[ment] and train[ing of] 100,000 great STEM teachers" (p. xi) and the creation of "1,000 new STEM-focused schools over the next decade" (p. xii). Several states

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responded to this agenda through the allocation of funds to set up STEM schools, which would ideally be staffed by teachers with strong expertise in STEM subjects. In the state of Ohio, legislators authorized seed grants for the establishment of new STEM public high schools.

In March 2008, a partnership in Cincinnati involving the local public school district, higher education institutions, corporations, and other agencies secured one of the seed grants. The decision was made to transform an existing urban high school serving large numbers of low-income African American students into the new STEM school. A planning team composed of lead veteran teachers, the new school principal, and a university researcher developed a school vision that emphasized college readiness through project-based learning (PBL) pedagogy (Hemmings, 2012; Rhodes, Stevens, & Hemmings, 2011). The team identified PBL as the optimal approach because it is regarded as central to innovative 21st century STEM education (Krajcik & Blumenfeld, 2006; National Research Council, 2000, 2012). Research indicates that PBL is an especially good approach for STEM education because it engages students in investigations of authentic real-world problems (Brickman et al., 2012; Duran & Şendağ, 2012). The approach also enhances critical thinking, independence, and innovation (Barak & Asad, 2012; Fishman & Krajcik, 2003; Krajcik, Czerniak, & Berger, 2003) as well as collaboration and organizational skills through inquiring questions, data collection, analysis, and reporting (Beckett, 2006; Bell, 2010; Hung, Hwang, & Huang, 2012; Isbell, 2005). It affords opportunities for fostering effective oral and written communication, information gathering, assessment, and analyses as well as students' curiosity and imagination in STEM specific content knowledge (Wagner, 2008).

Hughes High School, the new STEM high school in Cincinnati, was opened in fall 2008. A year later in 2009, the school was awarded an Innovative Technology Experiences for Students and Teachers (ITEST) grant from the National Science Foundation (NSF) to fund the design and integration of PBL CincySTEM ITEST projects into ninth and tenth grade science, technology, and STEM Foundations classes. The grant funded the purchase of digital backpacks called F-SETs, each of which contains the following equipment: a Texas Instruments (TI) Inspire calculator, a Livescribe pen and notebook, a laptop, an iPod Touch, an iPad, a Sony Cybershot digital camera, a Kodak digital video camera, and various science probes. The F-SET equipment could be used in the classroom as well as off-site for data collection, documentation, analysis, and product generation. Five CincySTEM ITEST projects—Energy Kaizenator, Global Climate Change, Global Water Challenge, Human Genome, and Roller Coaster—were designed and implemented by teacher teams.

The projects incorporated PBL pedagogical practices and were also guided by 5E Learning Cycle principles grouped under questions related to engagement, exploration, explanation, elaboration, and evaluation. The 5E Learning Cycle, created by Karplus and Thier (1967) for the Science Curriculum Improvement Study (SCIS), is a research-based model that consists of a recursive cycle of learning based on constructivist learning theory (Poomsripanon & Chitramvong, 2006). It has been shown to improve students' overall understanding of science and science concepts (Balci, Cakiroglu, & Tekkaya, 2006; Kowasupat, Jittam, Sriwattanarothai, Ruenwongsa, & Panijpan, 2012) and help students clarify their thought processes and correct misconceptions (Balci, Cakiroglu, & Tekkaya, 2006). Students participating in inquiry science guided by the 5E Learning Cycle have demonstrated better scientific reasoning abilities and positive attitudes toward learning (Kowasupat, Jittam, Sriwattanarothai, Ruenwongsa, & Panijpan, 2012). Applications of 5E Learning Cycle principles can also make learning activities more interesting, fun, motivating, and instructionally conducive for higher order thinking (Boddy, Watson, & Aubusson, 2003). This is

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especially true for activities involving the internet and other e-tools. As Su, Chiu, and Wang (2010) discovered, "e-learning materials based on the 5E are more beneficial than e-learning materials without 5E" (p. 402).

The overall purpose of the CincySTEM ITEST projects was to engage ninth and tenth grade students in innovative PBL and 5E science projects utilizing F-SET backpack equipment and develop a website featuring the projects (http://hughescincystem.com). The projects were developed by teacher teams over the course of the 3-year grant period. Team members and other teachers who were not involved in design work integrated the projects into their science, STEM Foundations, and technology courses. A qualitative evaluation study was conducted to find out if the projects increased student engagement and promoted learning and if they could be sustained over time. Although some projects were observably successful, teachers in other projects encountered challenges that were difficult for them to overcome. These challenges are well documented in the literature. What was revelatory in the study was how crucial teachers' accumulated experiences, peer support, and professional development were to success.

Challenges of Project-Based Learning in STEM Instruction

The PBL techniques and 5E Learning Cycle principles applied in the CincySTEM ITEST projects directly address the call to educate more STEM competitive students. They are rooted in the American philosophy of pragmatism through unfettered inquiry and emphasize learning in authentic contexts as the best environment for bringing schooling and the real world closer together (Barron et al., 1998; Bernstein, 1998; Blumenfeld et al., 1991; Dewey, 1916/1966; Krajcik & Blumenfeld, 2006; Peirce, 1958). However, the literature on PBL suggests that teachers who attempt such an approach in public school classrooms often confront a number of challenges related to administration and classroom supervision, appropriate expertise, community support, and tradition (Hosic, 1918; Kilpatrick, 1918). These challenges are endemic and help explain why despite significant advances in cognitive science and the availability of innovative instructional models large-scale efforts to align classroom instruction with philosophically pragmatic and theoretically constructivist approaches like PBL have been ineffective (Barron et al., 1998; Blumenfeld, Fishman, Krajcik, Marx, & Soloway, 2000; Cuban, 2009, 2013; Elmore, 1996; Sawyer, 2006). Howe and Berv (2000) point out that a constructivist view of learning does not neatly translate into a set of classroom practices. Those practices that do align with constructivist theory involve a radical change in teacher beliefs (Prawat, 1992). Transitioning to approaches like PBL involves incentivizing teacher change, respecting the complexities involved, and having reasonable expectations (Elmore, 1996; Towndrow, Silver, & Albright, 2010). From a pedagogical perspective, PBL must attend to real-world barriers experienced by classroom teachers as well as the manner in which teachers understand PBL practices. The success of PBL is dependent upon teachers' capacity and willingness to understand, enact, and sustain authentic PBL practices in context.

An insightful body of research relevant to PBL was conducted on an instructional innovation dubbed project-based science (PBS) that was developed and refined during a long-term collaboration between researchers at the University of Michigan and teachers employed in Detroit Public Schools. That research spans the last 15 years of the PBS initiative, which was based on an explicit model grounded in constructivist theory (Blumenfeld et al., 1991). It includes detailed case studies related to teachers' understanding and enactment of the model and frank discussions of the challenges encountered when the model was used as the basis for systemic and sustainable reform in urban schools (Krajcik, Blumenfeld, Marx, & Soloway, 1994; Ladewski, Krajcik, & Harvey, 1994; Marx et al., 1994; Marx, Blumenfeld, Krajcik, & Soloway, 1997). When the approach worked, as Marx et al. (2004) discovered in a 3-year study involving a large sample of urban middle school teachers and students, there were statistically significant gains in student learning that remained stable even during scale-ups. The Marx et al. study provides strong evidence that carefully orchestrated efforts at project-based pedagogical reform can work in urban settings. Other research indicates the use of technologies in science projects such as iPads and laptop computers can bolster achievement because it increases student engagement (Tinker & Krajcik, 2001). It is thus possible for science and other teachers in urban high schools to adopt a PBL approach that results in measurable student gains in learning and interest in STEM fields.

Research also shows that teachers need considerable support to successfully facilitate PBL. Regular meetings among researchers, content specialists, technology support staff, and teachers are critical to the effective enactment of project-based science (Blumenfeld, Krajcik, Marx, & Soloway 1994). This is particularly true for today's technology-intensive models (Boss & Krauss, 2007; Krajcik & Starr, 2001; Moursund, 2003; Uden & Beaumont, 2006), which necessitate professional development specific to technology integration (e.g. Higgins & Spitulnik, 2008; Mumtaz, 2000).

Krajcik et al. (1994) argue that teachers need to collaborate and to honestly communicate about the challenges they are experiencing related to classroom management and project implementation. Although such collaboration is time consuming, labor intensive, and can be expensive, it is the most effective avenue for building teacher capacity (Blumenfeld et al., 1994, 2000). Time for teacher collaboration becomes increasingly important whenever instructional innovations are the primary means for comprehensive school reform (Desimone, 2002). Even with such support, research suggests that teachers who enact PBS have difficulty managing a collaborative classroom and realizing the constructivist outcomes that such practices are theoretically expected to produce (Blumenfeld et al., 2000; Marx et al., 1994). These challenges are exacerbated by a variety of cultural barriers, management routines, and school or district policies that discourage collaboration, risk-taking, long-term assignments, and learning outside of the school building (Blumenfeld et al., 2000).

Case studies related to PBS also demonstrate that teachers enact PBS differently depending upon their beliefs about teaching and learning and their prior experience with educational innovations (Ladewski et al., 1994; Marx et al., 1994). In a case-based study of five teachers' reactions to a state-level reform in California's mathematics education, researchers found that some teachers changed their practice very much, some changed their practice very little, and some did not change their practice at all. The degree of changes depended upon teachers' beliefs and experiences and how they responded to the affective demands of managing an inquiry-based classroom (Cohen & Ball, 1990; Dreon & McDonald, 2012; Wallace & Kang, 2004). The teachers at Hughes High School confronted common challenges as they worked together to change how they taught and what they believed about teaching science through CincySTEM ITEST projects.

Implementation of CincySTEM ITEST Projects

With NSF-ITEST grant funding for F-SET backpack equipment and research-informed astuteness about the challenges associated with PBL, teams of teachers at Hugh High School proceeded to design and implement five CincySTEM ITEST projects—*Energy Kaizenator*, *Global Climate Change, Global Water Challenge, Human Genome,* and *Roller Coaster*. The projects were

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integrated into ninth and tenth grade science, STEM Foundations, and technology classes during the course of the 3-year grant. *Energy Kaizen,* the first project to be implemented, was designed to teach the fundamentals of energy audits and teach students how to identify energy kaizens in order to reduce costs and greenhouse gas emissions and improve operations in schools and homes. This project was piloted in spring 2010 by the two teachers who developed it and was implemented in spring 2011 in ninth grade by one returning teacher and one teacher who was new to the project. Both of these teachers implemented the project again in spring 2012 with minor revisions to improve its integration with the academic schedule, curriculum, and each instructor's teaching style. *Global Climate Change* focused on the causes and effects of global warming and how to develop an action plan designed to encourage the community to think globally and act locally. This project was implemented in fall 2010 by teachers who were new to the project. During the next year, one returning teacher took the lead and created more detailed course documentation to support the lessons and activities. The aim of the *Human Genome* project was to teach students the science of genetics and the social science of genealogy. This project was first taught in winter 2010–2011 by two teachers who were new to the project. When this project was implemented again in 2011–2012, the primary teacher was not in the school for the entire year due to a military deployment. The *Global Water Challenge* project concentrated on issues surrounding the availability of potable water while exploring local water and sewer facilities and operations. The project was implemented in 2010–2011 with substantial support from a local business partner to study water purification. In 2011–2012, the company no longer directly supported individual classes, and the course was redesigned to include field trips to a local water works and community walks to view water challenges at a more local level. The *Rollercoaster* project was added to the CincySTEM initiative during the 2011–2012 academic year. The ninth grade science teachers used it to introduce technologies that students would be using at the Hughes STEM High School and its application to project-based instruction.

Table 1
CincySTEM Timeline of Projects

Project	Class of 2013	Class of 2014
Rollercoaster	Not experienced	Fall 2011
Energy Kaizen	Spring 2010 (pilot; incomplete)	Spring 2011
Global Climate Change	Fall 2011	Fall 2012
Human Genome	Winter 2011	Winter 2012
Global Water Challenge	Intersession Spring 2011and Spring 2012 (Not all students)	Intersession Spring 2012 (Not all students)

There were highly innovative activities in all of these projects. For example, teachers in the *Energy Kaizen* project engaged students in the development of a Wikispace where they illustrated the strategies they used to calculate energy costs and consumption and also planned video tutorials on how to calculate an energy bill and implement cost-saving measures. For the *Global Climate Change* project, teachers facilitated students' preparation of a multimedia presentation in the form of an iMovie, a podcast, or a Wikispace using the F-SET backpack equipment. As part of this project, teachers also organized field trips to the Cincinnati Zoo and the Botanical Garden to provide opportunities for students to learn about different biomes and connections between the earth, plants, animals, and humans. Table 1 provides the project implementation timeline.

Teachers worked in a team organizational structure with common planning times allotted for ninth grade teachers all 3 years and common planning times allotted for tenth grade teachers only during 2010-2011. As grades were added to the school, experienced teachers were intentionally moved so that most teams included one returning teacher. The intent of this distribution of teacher experience and expertise was to induct new team members. Each team had at least one teacher who was new to the project each year. The ninth grade teaching teams had eight members over the course of the 3-year period with all teachers having at least 2 years of project experience by the end of the third year. The tenth grade teaching team had no full-time returning members in the second year. The only returning STEM Foundations teacher was deployed with the military during the second year and was replaced by a long-term substitute teacher.

As the summary in Table 2 shows, the ninth grade instructional team had four teachers working together for at least 2 years and two teachers collaborating for 3 years. These teachers were able to improve implementation of the lessons over multiple years. For the tenth grade instructional team, there was no continuity, thus new teachers were unable to make modifications based on the prior experiences of veteran teachers.

Table 2
CincySTEM ITEST Project Staffing (*Number of Years Teaching Projects*)

Planning Year	**Science** Facilitator 1	**STEM**	**Technology** Facilitator 2
Ninth Grade: Physical Science Projects			
2009–2010	Teacher 1 (1) Teacher 4 (1)	Teacher 2 (1) Teacher 5 (1)	Teacher 3 (1) Teacher 6 (1)
2010–2011	Teacher 1 (2) Teacher 7 (1)	Teacher 5 (2)	Teacher 6 (2) Teacher 8 (1)
2011–2012	Teacher 1 (3) Teacher 7 (2)	Teacher 5 (3)	Teacher 8 (2)
Tenth Grade: Biological Science Projects			
2010–2011	Teacher 9 (1) Teacher 4 (1)	Teacher 2 (1) Teacher 10 (1)	Teacher 8 (1)
2011–2012	Teacher 11 (1)	Teacher 10 (2)/Sub (1)	Teacher 12 (1)
Intersession: All Grades			
2010–2011	Teacher 1 (1) Teacher 4 (1)		
2011–2012	Teacher 1 (2)	Teacher 5 (1)	

The Evaluation Study

Data Collection

University-based external evaluators were contracted to conduct an evaluation of CincySTEM ITEST projects. Participants in the evaluation included twelve ninth and tenth grade teachers, one science and two technology facilitators, and their students (1,097 students in total). Data collected by the evaluators included the following: archival documents (e.g., lesson plans, project

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instructions, and students' project work), focus group interviews with teachers, Student Activity Feedback Forms (SAFF) that students filled out at the conclusion of projects; and classroom observations. The evaluation team had originally planned to use a modified Reformed Teaching Observation Protocol (RTOP) to observe at least three class periods per project. Initially piloted by The Evaluation Facilitation Group of the Arizona Collaborative for the Excellence in the Preparation of Teachers (ACEPT), the RTOP has been successfully tested for interrater reliability and construct validity. It has drawn from other sources, including NCTM Curriculum and Evaluation Standards and NRC National Science Standards, to establish its validity. Although the RTOP data collection tool would have shed light on the pedagogy used by the teachers implementing the CincySTEM projects, the instrument is cumbersome and requires observers to be in the classroom for the entire instructional time. That was not possible for these projects because they were taught over several weeks. Evaluators had to randomly select days when the projects were being taught so they could observe targeted aspects. Observations usually included one day when the teacher was delivering content, one day when the students were creating products, and another day when the students were presenting or demonstrating what they learned. To increase validity, two observers were in the same classroom whenever possible. After the observations were completed, evaluators produced a narrative summary of what they saw.

The evaluation team conducted a focus group of participating teachers each summer at the end of the academic year during regularly scheduled school professional development. These discussions occurred during the second day of summer professional development in June 2010, June 2011, and June 2012. The teachers were asked questions about classroom implementation; perceived student reactions and learning; support provided by the project team; future plans for using these projects, either in whole or in part; and any feedback for improving the CincySTEM Initiative ITEST project in the future. All qualitative data, including documents, focus-group discussions, and classroom observations, were reviewed and analyzed for emerging themes focusing on engaging students in CincySTEM ITEST projects informed by 5E Learning Cycle Principles, experience, peer support, and sustainability.

Findings

Successful projects. Observational data revealed significant pedagogical innovation in some but not all of the CincySTEM ITEST projects. In the most successful projects, students appeared to be learning science and were noticeably engaged in the assigned activities. This occurred in the *Human Genome* project in which students learned genetic science content and genealogy knowledge and used this knowledge to conduct laboratory experiments and create their own family genetic genealogies. In the *Rollercoaster* project, students created model rollercoasters using a JASON online educational module.[1] They learned about and applied scientific concepts in an iterative design process and then built rollercoasters to demonstrate applications. In the most successful rendition of the *Global Climate Change* project, the most innovative feature was the production of multimedia presentations in the form of Wikispaces, podcasts, and iMovies by students. Students were engrossed in these projects, and their engagement was heightened by the use of F-SET digital backpack equipment.

The results of Student Activity Feedback Form (SAFF) that students filled out at the conclu-

[1] Founded in 1989 by Dr. Robert D. Ballard, JASON is a nonprofit organization managed by Sea Research Foundation, Inc., which is governed by Sea Research and the National Geographic Society (http://www.jason.org).

sion of projects indicated that the digital backpack equipment enhanced learning experiences. The SAFF was administered to find out how much students were using equipment and if they felt the technologies were helping them learn science. Results on items asking whether equipment enhanced learning were generally positive with mean agreement ratings ranging between 3.40–4.38 out of 5. Written responses to SAFF open-ended questions were also encouraging. Students described how much they learned about global warming and greenhouse gases in different countries, the positive and challenging aspects of teamwork, doing research and presenting findings on PowerPoint slides, and assuming different roles in the project. With regard to the F-SET digital backpack equipment, students reported using the TI Inspire calculators, Kodak video cameras, and iPads most of the time.

These findings show the ways in which the most successful projects were pedagogically innovative, engaged students, and involved constructive use of F-SET digital backpack equipment. However, significant discrepancies between the most successful projects and other projects were also revealed in the study.

Keys to success. Some projects, simply put, were much more successful than others. One key factor in the study was teachers' accumulated experience. Teachers who were assigned to the same projects for all 3 years accumulated the experience they needed to make the projects progressively better. The *Energy Kaizen* project is a good example of this. This project was launched during the first year as a pilot, and although it was not carried through to completion, it did yield a pedagogical baseline for what did and did not work. The teacher who facilitated the pilot was assigned to that project again during the second year. She completed the project and expanded students' data collection from locations in the school to each student's home. During the third year, she managed to connect energy concepts discussed in the *Energy Kaizen* project with those in the *Rollercoaster* project. As this teacher accumulated experience, she improved and expanded the project and, as an added value, created conceptual links to other projects. She became an expert who fine-tuned the project and moved it progressively into new realms.

The crucial importance of accumulated experience was also evident in the use of F-SET backpack equipment. As teachers became more familiar with the equipment and how to incorporate it into activities, they became more adept at providing students with guidance for how to use the equipment to enhance their learning. During the second year of the *Global Climate Change* project, teachers provided students with a detailed packet of instructions to keep them engaged during their zoo trip. These instructional packets were designed to incorporate the F-SET backpack equipment provided to students. Evaluators observed students taking notes using the iPads and LiveScribe pens and paper as well as documenting their experiences with still and video cameras. Through more adept use of equipment, teachers were able to make changes to improve the curricular materials and exert a positive influence on student behavior.

Another key reason for why some projects were more successful than others was teacher peer support, especially when more experienced teachers worked directly with inexperienced colleagues (those who were new to the project). The teachers who worked together on design teams and then facilitated projects for 2 to 3 years were significantly more innovative and successful then teachers who were not on the design team or did not have years of accumulated experience. A few but not all of the teachers who were new to the project were mentored by experienced teachers. Such peer support through mentoring not only helped novice teachers overcome challenges but also ensured continuity in the development and delivery of curricular materials.

Much of the experienced teacher peer support for nonexperienced teachers occurred during common planning times that were built into the schedule. During the school's inaugural academic

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year (2009–2010) in which the *Energy Kaizen* project was piloted, ninth grade instructional teacher teams had 45 minutes of interdisciplinary planning time daily. During the 2010–2011 academic year, the ninth and tenth grade instructional teams had common planning time of 45 minutes daily. In 2011–2012, only ninth grade instructional teams had a common planning time of 50 minutes daily. The intersession teachers worked together for 60 minutes each week from January through April. The reduction in common planning time had a notably detrimental impact on projects facilitated by inexperienced teachers who were being left alone to figure out how to implement projects by the third year. In fall 2010, teachers who were assigned to the *Climate Change* project did not have peer support. Their curricular materials were not very detailed or clear, which caused students to become unfocused as they collected data at the Cincinnati Zoo and Botanical Garden. Students' final projects had correct factual information, but the information was not connected to the bigger picture of climate change's impact on biomes, plants, and animals. During the second year, the project was primarily led by just one teacher, which also resulted from the loss of common planning times and teacher continuity from year to year.

A third key to success was the provision of professional development (teachers were compensated for their participation by grant funds). The first professional development session occurred during summer 2010 for 3 full days during which design team teachers worked on developing projects. During the 2010–2011 academic year, teachers facilitating projects held monthly meetings to discuss implementation. The professional development sessions that took place the following summer focused on design, implementation, and forging linkages with the zoo, corporations, and other external partners involved in the projects. A 2-week whole-school professional development session was followed by teachers working in pods for 40 hours over the remainder of the summer. During the 2011–2012 academic year, the project team used a coaching model to work with grade-level teams during the year. The teams worked to better connect the projects to semester exams and state benchmarks and standards.

During the course of professional development, data from the SAFF was used to determine the extent to which F-SET equipment was being utilized. Results indicated that not all teachers involved in the CincySTEM projects were utilizing the equipment fully. There was especially low usage of the iPod Touch and iPad due to a lack of sufficient teacher expertise. A graduate assistant from a local university was hired to help teachers who needed professional development in learning to incorporate digital technology tools into their project activities. The project team also added new sections to the CincySTEM project development template to encourage teachers to purposefully plan for incorporation of digital backpack equipment and revamped summer professional development so that teachers would receive more relevant training. All of these aids helped teachers better integrate F-SET digital backpack equipment into activities.

Observations indicated that teachers who participated in professional development were significantly more innovative in their science instruction than those who did not. There was much more hands-on learning, higher student engagement, and more authentic scientific investigations of contemporary problems in the projects that they facilitated. Teachers made better use of F-SET equipment to foster skills, data collection, interpretation, and learning. Students in projects facilitated by teachers who were not involved in professional development were noticeably disengaged and disruptive, especially in classrooms in which teachers started to rely on worksheets. Professional development was a major part of the difference between teachers who were able to engage students in the CincySTEM ITEST projects and those who were not.

Challenges to success. Some teachers experienced challenges with insufficient time and crossdisciplinary content expertise. Interviews with teachers regarding challenges to sustainability of the CincySTEM ITEST project revealed that some teachers wished that they had more time to document the complexity of their work on the project website. For example, one teacher said that managing the ITEST projects for her students was her primary concern, but she did not feel she had time to provide a detailed road map for other teachers to follow her work. She describes the CincySTEM ITEST initiative as a "grand opportunity" that needed more time than they had for planning, documentation, reflection, and improvement. She said, "The amount of stuff that you need to do is exponential to the amount of time that you actually have to do it." Several other teachers in the study expressed the same concern.

The crossdisciplinary nature of the CincySTEM ITEST projects presented another significant challenge for the participating teachers. As we see in the following excerpt from the interviews, teachers said that projects required technology, language arts, mathematics, and science knowledge, which required coordination and collaboration with teachers in different content areas who may or may not have the same vested interest in the projects.

> There were actually pieces that should be facilitated in the technology class; pieces that should be facilitated in the language arts class; and pieces that should be facilitated in the math class, which means that you have to coordinate and collaborate with those teachers who may or may not have the same vested interest in the project that you do.

Collaboration was also made difficult by a lack of shared content knowledge among STEM educators, each of whom has been trained in one primary discipline. Several teachers reported that their conversations with project colleagues became most challenging when related to the content of one another's discipline of expertise.

Conclusion

We know from prior research that the design and implementation of pedagogical innovations in STEM instruction often require new teaching tools, ample professional development, and continued support. Teachers need expert knowledge and confidence in technology use to be able to engage students (Tinker & Krajcik, 2001). They benefit from regular meetings with content specialists, technology support staff, and other teachers for successful enactment of technology infused PBS (Boss & Krauss, 2007; Higgins & Spitulnik, 2008; Krajcik & Starr, 2001; Moursund, 2003; Mumtaz, 2000; Uden & Beaumont, 2006). The success of PBL projects in particular depends upon prior teaching and learning experiences with educational innovations (Ladewski et al., 1994; Marx et al., 1994), especially experiences with inquiry-based pedagogical practices (e.g., Cohen & Ball, 1990; Dreon & McDonald, 2012; Wallace & Kang, 2004). Teachers also need the support of colleagues (Tinker & Krajcik, 2001), and work on projects goes more smoothly if it is incentivized (Elmore, 1996; Towndrow, Silver, & Albright, 2010).

The findings of the evaluation study of CincySTEM ITEST projects confirm prior research, but they also contribute valuable new insights into effective ways to design and implement innovative PBL projects. Among key insights are the vital importance of teacher experience accumlated through years of carefully thoughtout implementation, experienced teachers' peer support of inexperienced teachers, and professional development in which teachers learn from each other and from outside experts. These features of the CincySTEM intiative enabled teachers to meet most of the challenges commonly associated with PBL projects and to improve projects over time. None of this would have been possible without the organization of teachers into design and implementa-

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tion teams and the allocation of time for team members to work together. Teams during the first 2 years had common planning times built into their school schedules. Some of the CincySTEM ITEST projects progressed as the years progressed because the same teachers were assigned to them. These teachers accumulated experience that they could use to support colleagues who were new to the project during planning times. The team planning and organizational structure made it possible for teachers to design, implement, improve, and transmit successful CincySTEM PBL projects.

This structure deteriorated as the school grew and grant funding ended. Nevertheless, the CincySTEM ITEST projects have left a legacy. Many of the curricular materials developed during the 3-year period of the grant remain as intact projects or discrete activities. They are currently in use by eighth, ninth, and tenth grade teachers and students. Changes in Core Content Standards have led to parts of the *Global Climate Change* project being used in either the ninth- or tenth-grade science courses, and the ninth-grade biology course is using pieces of the *Human Genome* and *Global Water Challenge* projects. The *Human Genome* project activities also continue into the tenth grade science curriculum. The *Energy Kaizen* and *Rollercoaster* projects are now more aligned with the eighth grade physical science standards. Along with these core courses, 2013 intersession opportunities have utilized aspects of these projects. For example, one of the CincySTEM participating teachers had students conduct an energy audit of his house, and an architecture-focused intersession used software first identified as part of these projects and the F-SET equipment.

In addition to specific curricular materials, the project website continues to be active. It contains artifacts and is linked to the school website so that teachers have continued access. The project provided a process for Hughes STEM High School teachers to continue to check out and use the technology. Professional development has given teachers the skills and confidence to integrate technology into their instruction in a more meaningful and productive fashion. The CincySTEM ITEST projects created a curricular foundation and resources to encourage the types of projects that support students' STEM career aspirations. The challenges presented learning opportunities for the project team. Three years of work on the initiative helped solidify working relationship among teachers, school and district administrators, and university researchers and evaluators for further collaboration. That is one of the best legacies of all.

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A Process Model of the U.S. Federal Perspective on STEM

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Abstract

Although advocacy for better science, technology, engineering, and mathematics (STEM) education has a long and distinguished history in the United States, the recent emphasis has included strong rhetoric and concomitant funding. Policy makers legislate as though STEM is clearly defined. Yet, the concept remains nebulous, which limits the nation's capacity to act in a strong and uniformed manner to address societal challenges. In this study, the authors used grounded theory methods to synthesize and interpret the federal perspective that defines STEM in the United States. The resulting theory is a model that includes five core processes: recruitment, recapture, retention, quality assurance, and quality control. These processes interact to support the system in achieving its goal of producing a qualified future workforce. Such a model has implications for advancing the overall goals of STEM as well as further research and development on the components of the model itself.

Keywords: Grounded theory; Process model; STEM education

Over the past two decades, interest in the science, technology, engineering, and mathematics (STEM) professions has increased dramatically. In fact, some would go back a bit further in time and argue that the launch of the Sputnik satellite was the event that ushered our national focus on STEM (Breiner, Harkness, Johnson, & Koehler, 2012; Sanders, 2009). Though advocacy for better science and mathematics education have a long and distinguished history, the recent emphasis on STEM has included strong rhetoric by legislators, followed by concomitant funding by the U.S. federal government. Policy makers speak and legislate as though STEM is clearly defined and well understood. However, the current environment is lacking in clear guidance and is imbued with personal opinion and the voices of special interest groups (Bybee, 2010; Herschbach, 2011; Raju & Clayson, 2011; Sanders, 2009; STEMPower, 2015). In initiatives such as the *Educate to Innovate* campaign—in which President Obama identified the national priorities as increasing STEM literacy, improving the quality of mathematics and science teaching, and expanding education and career opportunities for underrepresented groups (White House, 2009)—there is a clear sense of a national driving force, signifying that we are in the midst of a STEM movement (National Science Board [NSB], 2007; Thomasian, 2011).

Table 1
Data Sources by Category With Illustrative Examples

Category	Number	Examples
Report issued from the federal government	29 (28%)	National Science and Technology Council, Committee on STEM Education. (2013). *Federal science, technology, engineering, and mathematics (STEM) Education: 5-year strategic plan*. Washington, DC: Author. President's Council of Advisors on Science and Technology. (2010). *Prepare and inspire: K–12 education in science, technology, engineering, and math (STEM) for America's future*. Washington, DC: Author.
Report issued by a corporation or other private entity	25 (24%)	Coble, C., & Allen, M. (2005). *Keeping America competitive: Five strategies to improve mathematics and science education*. Denver, CO: Education Commission of the States. Thomasian, J. (2011). *Building a science, technology, engineering, and math education agenda: An update of state actions.* Washington, DC: National Governors Association Center for Best Practices.
Report issued by an entity affiliated with a college or university	9 (9%)	Morrison, J. S. (2006). *Attributes of STEM education: The student, the school, the classroom. TIES STEM Education Monograph Series.* Cleveland Heights, OH: Teaching Institute for Excellence in STEM. Sturtevant, D., & Nguyen, L. (2011). *Understanding STEM education as a complex system*. Cambridge, MA: Emtect Solutions. Retrieved from http://www.micouncil.org/documents/Sturtevant_STEM.pdf
Peer-reviewed journal articles	34 (33%)	Breiner, J. M., Harkness, S. S., Johnson, C. C., & Koehler, C. M. (2012). What is STEM? A discussion about conceptions of STEM in education and partnerships. *School Science and Mathematics*, 112(1), 3–11. doi:10.1111/j.1949-8594.2011.00109.x Katehi, L., Pearson, G., & Feder, M. (2009). The status and nature of K–12 engineering education in the United States. *The Bridge: Linking Engineering and Society*, 39(3), 5–10.
Websites, blog posts, or webinars	7 (7%)	Mangan, K. (2013, February 11). Community colleges respond to demand for STEM graduates. *Chronicle of Higher Education.* Retrieved from http://chronicle.com/article/Work-Force-Demand-for-STEM/137231/ Zipkes, S. (2012). The new wave of STEM-focused schools. [Webinar]. Retrieved from http://www.doe.in.gov/sites/default/files/ccr/inclusive-stem-high-schools.pdf
Total	104	

For some, the goal of STEM is nothing more than the renewed effort directed towards the literal embodiment of the disciplines that comprise the acronym. For example, Eberle (2011) suggests that the STEM movement is currently being interpreted as merely a new name for the existing,

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fragmented way that mathematics and science courses have been taught. However, Lantz (2009), Bybee (2010), and others are calling for STEM to take on a more robust, multidisciplinary form, as illustrated by the following quote.

> The United States needs a broader, more coordinated strategy for precollege education in science, technology, engineering, and mathematics (STEM). That strategy should include all the STEM disciplines and address the need for greater diversity in the STEM professions, for a workforce with deep technical and personal skills, and for a STEM-literate citizenry prepared to address the grand challenges of the 21st century. (Bybee, 2010, p. 996)

In order for the current STEM movement to achieve anything close to Bybee's vision, we contend that it is important to first understand the perspective and issues that define the current context. Therefore, the goals of this study were to: (a) develop a model to explain STEM in theoretical terms, (b) define and describe the properties of the model components, (c) illustrate the sociopolitical context under which the model emerges, and (d) delineate the consequences of our model for future innovation, research, and development.

Accordingly, we employed grounded theory methods to synthesize and interpret the federal perspective that underpins the current STEM movement in the United States. The resulting theory is a process model that defines and describes the core functions supporting the system. Process models are created to support the practice of design and thus have utility for creating solutions that are intended to address underlying issues (Rolland, 1998). Defining STEM in these terms affords an opportunity to advance research, development, and evaluation by moving beyond the rhetoric of why STEM is important and what it should be to better articulate it as a formal, logical, goal-directed system thereby beginning to address the problem more systematically (Confrey, 2006).

Before detailing our study, we find it important to note that the ideas presented here are not our vision for STEM. Instead, they represent the result of our use of grounded theory methods to interpret the issues and perspectives that make up the context for STEM as a national priority. Following the description of our methodology, we present a definition of STEM that was constructed through our analysis as well as our model with details on the five core processes. We conclude by discussing future research and development related to the model components as well as implications for advancing the field.

Methodology

This study used Charmaz's (2006) method of constructivist grounded theory to develop a model for STEM by interpreting the U.S. federal perspective that underpins the movement. The use of grounded theory afforded analyses that emphasized *action* and *process*, themes consistent with a movement focused on a national call to action (NSB, 2007). We used Krogstie's (2012) definition for a process: "a collection of related, structured tasks that produce a specific service or product to address a certain goal for a particular actor or set of actors" (p. 315). We began with the broad question: What defines STEM in the United States? As our analysis progressed and our definition of STEM was refined, the following questions emerged and provided additional focus for our work:

- What basic processes compose STEM?
- How are the processes related to one another?
- How are the processes related to the perspective that STEM is a solution to a problem?

Data collection was guided by the logic of theoretical sampling: Namely, we began with an initial set of documents, developed our theory, and then strategically sought out additional research and resources to further refine the theory (Creswell, 1998). For example, we began data collection and analysis with a formal writing task in which we reviewed a collection of references that included federal reports (e.g., President's Council of Advisors on Science and Technology [PCAST], 2010), websites of STEM coalitions (e.g., Triangle Coalition), federal statistics (e.g., NSB, 2010), and a special issue of *School Science and Mathematics*, an educational research journal, that focused on STEM (Johnson, 2012). Individually, we selected subsets of these sources and constructed two detailed arguments: a pro-statement defining STEM and a con-statement arguing against it as a unifying theme. These writing samples were reviewed and synthesized into our initial set of codes, which included collaborations, project-based learning, socioscientific issues, effective pedagogy, policy, applications, multidisciplinary, lack of participation, accountability, integration, literacy, and technical skills.

Data were limited to published and publically accessible documents and reports prior to 2014 from reputable public and private sources as well as articles from peer-reviewed journals that addressed STEM explicitly (Table 1). Chronologically, the earliest data source used was a 1993 publication from the Scale and Effects of Admissions Preferences in Higher Education (SEAPHE) project at UCLA titled *Undergraduate Science Education: The Impact of Different College Environments on the Educational Pipeline in the Sciences* (Astin & Astin, 1992). The majority of data sources were published in 2011 (23%), and as a supplement to this article, we have provided a reference list for the 104 sources that were used in our analysis. With respect to the information contained in our sources, we focused on identifying: the parameters, authority, and meaning from the perspective of various participants and stakeholders; the missing and implicit messages; the intended audience and beneficiaries; and how this information might affect action (Charmaz & Mitchell, 2001).

We considered all data to be situated in a context and used them as objects for analytic scrutiny by dissecting the purposes, authors, and how they were produced (Charmaz, 2006). Each datum was identified by applying our criteria to search results from the Internet, academic research databases (e.g., EBSCO, Academic Search Premier), and a review of the cited references in existing documents. For example, our analysis of the initial sources revealed two pivotal documents produced by the President's Council of Advisors on Science and Technology (PCAST), Prepare and Inspire (2010) and Engage to Excel (2012). These documents first established the problem of a projected lack of human capitol as a national issue and then articulated the federal response for improving K–12 and higher education, respectively. The frequent citation of these documents in subsequent reports led us to focus explicitly on the role of federal policy.

Data were collected and analyzed, and the results were used to refocus on the collection of new data. Following the method of grounded theory, our research problem continuously shaped our analysis. For instance, after having read Mertens and Hopson's (2006) argument for the use of a social agenda and advocacy in evaluation, it was clear that our description of the quality control process needed to be expanded not only to address the people leaving the system but also to include formative elements during matriculation that feed back into the system. The work of Mertens and Hopson (2006), as well as the other articles in a special issued dedicated to issues of evaluating STEM projects, provided the characteristics for adding a fifth core process to our model, quality assurance: "to provide the information required to indicate whether the process and structures through which outcomes and services are produced are operating effectively, and to provide recommendations on ways in which these processes can be improved" (Cuttance, 1994, p. 102).

A constant comparative method formed the foundation of our analysis (Strauss & Corbin,

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1998). We engaged in an ongoing conversation over approximately three months that focused on identifying and evaluating existing and emerging evidence in relation to our argument for a process model and our rationale for the distinction among the processes. The heuristic for our approach, which was consistent with the algorithm provided by Taber (2000), involved seeking data, describing the perspective and processes that were being illustrated, addressing our fundamental questions about what was happening, and then developing theoretical categories in order to understand the information presented in each document (Charmaz, 2006). Each round of coding and discussion focused our analysis and advanced our theoretical sampling.

Analysis Heuristic

Our analysis proceeded through three phases of coding: open, axial, and selective. Data were first open coded based upon emergent themes. Examples of open codes included: developing technical skills, preparing for future employment, and using strategies to increase achievement. In order to establish the properties of individual codes, each new data source was compared to the previous data source. Open coding led to two key decisions related to the direction of our research: (a) our explicit focus on the role of the federal government in shaping the definition of STEM and (b) our choice to use STEM education synonymously with STEM. Our explicit focus on the role of the government was based upon our recognition of the historical emphasis of federal policy to introduce change in a system in order to create a more literate, competitive, and employable citizenry while addressing a host of national problems (Atkin & Black, 2003). Our decision to use STEM as a synonym for terms such as STEM education arose from our finding that the terms were consistently used across all documents with one or more of the following concepts: an educational problem (Kuenzi, Mathews, & Mangan, 2006), an educational solution (Coble & Allen, 2005), or an education-related outcome (National Research Council [NRC], 2011).

Axial coding involved clustering codes and creating categories such as goals, target audience, and example initiatives. During this phase, we developed our working definition of STEM, which was later used as a vehicle for selective coding. As we characterized the overall activity, our emerging axial codes fell under two main categories: (a) processes related to maintaining the number and diversity of people in the formal educational system and (b) examples of initiatives (i.e., designed activities that were often funded) influencing these processes. As we reviewed the various initiatives, we identified attributes common to the processes and later classified them as possible cross-cutting concepts. In order to refine our developing model, the themes expressed in those documents were compared with previous codes and the emerging characteristics of a collection of processes.

Selective coding involved the formal articulation of the core processes and an initial model to represent our developing theory. Resulting from our analysis, we constructed two formal products, a definition of STEM and a model to represent our theory that included five core processes: (1) recruitment, (2) recapture, (3) retention, (4) quality assurance and (5) quality control. As cycles of data collection and analysis were completed, these products were assessed and refined. Thus, our emerging theory guided our ongoing data collection, which served to focus our research and enhance our theory (Taber, 2000). For example, we tested our assumption that all STEM initiatives could be characterized as having a primary focus on one of the five core processes by comparing the model against abstracts for funded projects under the Mathematics and Science Partnership (MSP) program of the National Science Foundation. Finally, we addressed theoretical saturation by presenting our findings in two separate professional venues. Figure 1 illustrates our analytical method by defining the elements of recruitment as one of the five core processes.

Research questions	Example codes	Categories	Defining elements of recruitment
What defines STEM education in the United States?	Developing technical skills; Preparing for future employment; Using strategies (i.e., inquiry, PBL) to increase achievement; Emphasizing mathematics and science education; Providing authentic experiences (e.g., internships, research); Inconsistently executing in K–12; Fragmenting into separate disciplines; Inadequate preparation for postsecondary study; Lacking initiatives utilizing research-grounded strategies to increase presence of underrepresented students	Goals	Increase diversity of those in professions; Create positive identities; Defy prevailing stereotypes about who can succeed; Prepare all students to be literate citizens; Prepare students for postsecondary study
		Target audience	Pre K–12 students; Students entering undergraduate studies; Underrepresented students
What basic processes compose STEM?	Seeking students, encouraging to pursue study; Using engaging instruction to increase underrepresented students' access; Curricula connect to society's most pressing relevant issues; Offering students financial incentives and extracurricular resources	Curriculum & instruction	Integrated/interdisciplinary; Coordinated sequencing of subjects; Sustained instruction; Problem and project-based; Cooperative and collaborative; Infuse technology; Emphasize formal and applied/practical knowledge
		Current initiatives	Inclusive high schools; IL Mathematics and Science Academy; NC School of Science and Mathematics; Summer bridge programs; Project Exploration; Youth Exploring Science (YES); Early College high schools; Meyerhoff Scholars
How are the STEM processes related to one another?	Offering tracks for focused career and technical education; Decreasing time taken to earn college credits; Bolstering readiness through bridge programs; Offering extended-day activities; Mentoring with professionals	Enduring issues and questions	Transparency and accessibility to support scaling and R&D; Need for academically advanced courses in focused schools; Significant financial support for postsecondary study to offset low-income background.

Figure 1. An illustration of the analytical method from research questions to articulation of the defining elements of the process of recruitment.

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We begin our discussion of results with the constructed definition of STEM, one based upon a core idea from our analysis, that STEM is an ill-defined solution to a national problem. This is followed by a description of the five core process model in which each of the processes is detailed and we explain our ideas about relationships among them. Finally, we conclude by discussing future research and development on the components of our model as well as implications for advancing STEM.

Results

STEM Is a Solution to a Problem

Highly technical jobs require an ample supply of qualified workers. Because the projected future demand for such jobs outpaces the limited supply of qualified workers, STEM is espoused as a solution to this problem (Coble & Allen, 2005; National Academy of Sciences, National Academy of Engineering, & Institute of Medicine, 2007; Lewis, 2006; Association of American Universities, 2006; Business Roundtable, 2005). In order to sustain economic growth, national security, an informed electorate, and endure as a global leader, the United States needs to further develop and maintain a qualified workforce (Obama, 2011). Economic analysts forecast that the United States will need one million more STEM graduates over the next decade (Langdon, McKittrick, Beede, Khan, & Doms, 2011). These graduates will be working in careers that are difficult to predict, largely due to the influence of technology, and this ambiguity has contributed greatly to the confusion and seemingly lack of focus for STEM. However, there is high confidence that these careers will include K–12 teachers, scientists, engineers, technicians, health care professionals, and higher education faculty (Sommers & Franklin, 2012). According to reports such as *Rising Above the Gathering Storm* (National Academy of Sciences, National Academy of Engineering, & Institute of Medicine, 2007), the economic, technological, and general well-being of the United States is dependent on educational programs that can prepare engineers and scientists for today's innovative and dynamic global economy. Therefore, from a U.S. federal perspective, the goal of STEM is more accurately described as a movement to increase the volume and quality of individuals ready to enter STEM jobs. Though the metaphor is debated (Sanders, 2009), STEM is often described as the pipeline that makes this volume and quality possible (Astin & Astin, 1992; Kuenzi et al., 2006).

The current federal solution to the problem that exemplifies STEM is a goal-directed, long-term systemic strategy utilizing policy and economic incentives to guide and enact a response to the evolving issue (NSB, 2007; Obama, 2011). The goal is a sustainable system that produces and maintains a qualified workforce (Carnegie Corporation of New York/Institute for Advanced Study, Commission on Mathematics and Science Education, 2009; NSB, 2007). Therefore, we offer the following as emergent from our analysis, a definition of STEM that we use synonymously with STEM education:

> **STEM** is an enterprise focused on maintaining an adequate number and diversity of students who are in good standing and pursuing a formal academic credential in a field involving the use of science, technology, engineering, or mathematics.

This definition is grounded in our data and has been modified over time as our theory developed. For example, our use of the word *enterprise* is intended to avoid the limitations of the pipeline metaphor (Mervis, 2012) while recognizing that this difficult undertaking includes a collection of disparate entities, requires bold initiative, and involves a degree of risk. Also, we propose that the economic climate influences the visibility of STEM, but the enterprise is defined by government policy emerging as output of the political system. Thus, STEM is a sociopolitical entity that is based upon a problem with social ramifications and influences but is also defined and funded through the U.S. political process. The emphasis on the formal academic system and credentialing is consistent with the role of U.S. government but also recognizes the importance of formal learning for supporting our capacity to innovate (PCAST, 2010). Further, a highly educated populace serves the system in two ways: It addresses the problem of an underprepared future workforce, and it also ensures a more educated electorate that is capable of understanding their needs and using their votes to support elected officials that favor maintaining the focus and funding. Our broad and somewhat vague definition for "a formal academic credential in a field" is purposeful and recognizes the ambiguity of projecting future jobs. Thus, the emphasis for a national movement has to be on producing credentialed people for future jobs, not simply qualified people for current jobs (Kuenzi et al., 2006).

The Five Core Process Model

Figure 2 is a representation of our grounded theory, the five core process model of STEM. This model recognizes the enterprise as consisting of five core processes: recruitment, retention, recapture, quality assurance, and quality control. The model is based upon the enactment of STEM as a function of the formal educational system, consisting of the two primary components, pre-Kindergarten through Grade 12 (preK–12) and higher education (13–20+). The form of the model is partially dictated and defined by the constraint of time and age in the preK–12 component, meaning that once students advance beyond a defined age range they no longer have access to that component of the system. However, assuming that an individual meets the admission requirements, higher education remains open, regardless of age. For the five core process model, this implies that the preK–12 component is linear and strictly defined by age and time but the higher education component is nonlinear and less constrained. The constraint of age underlies the distinction between the processes of recruitment and recapture and how they are applied within our model. The process of *recruitment* emanates from our assumption of a single, first-time career focus and is applicable from preK through the first years of undergraduate education. By defining higher education as including the Grade 20+, we recognize its role across the lifespan for just-in-time training as well as longer term career and workforce education. The process of *recapture* emphasizes the intent of bringing people into the system who are currently involved in another career. The processes of retention, quality assurance and quality control are integral and applicable throughout the enterprise. Table 2 provides an overview of the participants, emphasis, interventions, and programs for each process that are then described in greater detail in the following sections.

Educational System	PreK–12			Higher Education		
Grade Level	PreK	Kindergarten–8	9–12	13–15	15–20	20+

Five Core Processes of STEM	Recruitment	Recapture
	Retention	
	Quality Assurance	
	Quality Control	

Figure 2. A model for STEM that includes five core processes in relation to the components and grade levels of the formal educational system. The model illustrates how the processes change as a function of the current or available grade level for a participant.

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Table 2
Overview of the Five Core Processes of STEM

Process	Participants	Emphasis	Nature of interventions	Example program
Recruitment	Children to young adults; preK through the first years of undergraduate education.	Fostering an interest in STEM as a first-time career.	Formal and informal educational programing, delivered outside of school hours.	Building Opportunities and Overtures in Science and Technology <http://sites.duke.edu/boost>
Recapture	Adults	Publicizing and affording STEM as a second career alternative.	Career and workforce education.	Fast Forward New Mexico <http://www.fastforwardnm.org>
Retention	All ages from preK through adult.	Maintaining the number and diversity of students.	Academic support programs targeting known deficiencies and barriers.	High Tech High School <http://www.hightechhigh.org/>
Quality assurance	All ages from preK through adult.	Using feedback from evaluation to improve the function of the system.	Just-in-time training focused on maintaining quality. Professional development.	Kentucky P20 Innovation Lab <http://p20.education.uky.edu/>
Quality control	All ages from preK through adult.	Summative evaluation of the system's ability to meet its goals.	Assessing the knowledge and skills of the graduates, the current job market and the projected opportunities.	The STEM Research and Policy Brief Series <http://www.bhef.com/publications/research-briefs.asp>

Note. This table includes participants, emphasis of each process, nature of interventions used within each process, and example programs from across the United States.

Next, we discuss the processes individually, beginning with recruitment and recapture that serve the same goal, to bring learners into STEM. Though similar, the two processes can be differentiated by the applicable range of ages, career background, and potential entry points into the formal education system. These attributes ultimately influence the activities and strategies employed in each process as well as the short and long-term options available to participants.

Recruitment

Because children and young adults enter and leave STEM over a relatively fixed age range and linear time period, the process of recruitment is unique to preK–12 education and the first years of undergraduate, postsecondary education. Recruitment initiatives aim to increase the number and diversity of people in STEM, prepare students for their future careers, and increase knowledge and achievement (NRC, 2011). To achieve such goals, students are often sought out and actively encouraged to apply to special programs, courses, and schools (Leggon & Pearson, 2009; Schultz et al., 2011).

In response to longstanding achievement disparities stratified by race and socioeconomic status (NAEP, 2009; Aud et al., 2010; National Science Foundation, Division of Science Resources Statistics [NSF], 2011), a large focus of recruitment activities has been on enhancing underrepresented students' interest in STEM (Building Opportunities and Overtures in Science and Technology [BOOST] Science Program, 2012; Project Exploration, 2013; Saint Louis Science Center, Youth Exploring Science Program, 2012). Problem-based learning and project-based learning are often promoted as instructional strategies and curriculum interventions that can serve as a tool for recruitment (Jones, Rasmussen, & Moffitt, 1997; Verma, Dickerson, & McKinney, 2011). Recruitment can occur via targeted strategies (Kaser, 2006; Means, Confrey, House, & Bhanot, 2008), including early college high schools (Early College High School Initiative, 2012; Goldberger, 2008) and bridge programs (Means et al., 2008), or through the use of specific selection criteria. At the postsecondary level, targeted recruitment often includes providing incentives such as stipends, research and mentoring opportunities, enrichment programs, and supplemental instruction to underrepresented students (Schultz et al., 2011).

Similar to recruitment, the recapture process is intended to bring adult students into STEM. With its exclusive focus on adults, a responsive recapture process is a critical component for addressing the inherent ambiguity of projecting future jobs and career opportunities. Unlike recruitment, recapture focuses on recruiting individuals who are outside of a formal education setting and beyond the linear timeframe of K–12 education.

Recapture

Recapture involves initiatives aimed at encouraging and incentivizing STEM as a means to a viable second career. Recapture is a unique process because it inherently targets nontraditional students. A nontraditional student as one who satisfies one of the following characteristics: older than a typical age, part-time student, full-time worker, having dependents, being a single parent, or being the recipient of a General Education Degree (GED) or high school completion certificate (Aud et al., 2012). Nearly 40% of all college students are classified as nontraditional (Tripp, 2011), and six million college students are 25 or older (U.S. Department of Education, Federal Student Aid, 2015). With such a large percentage classified as nontraditional, institutions and initiatives are focusing on the process of recapture, introducing individuals back into the system or providing them tools to reenter after an initial exit.

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Regardless of the reasons for or point of exiting, the process of recapture provides an opportunity for reentry into STEM and the potential for employment. Fulfilling the vision of an access point for the broadest range of adults requires a degree of responsiveness. Entrance requirements, prerequisites and degree completion requirements, such as significant numbers of credit hours, all limit the number of options for participants.

The methods of recapture can vary depending on the point of reentry. The GED is a primary mode of recapture that, since 1942, has provided those who did not obtain a high school diploma with a method of gaining a high school equivalency diploma (GED Testing Service, 2012). Workforce development programs provide training and assistance to job seekers (U.S. Department of Labor, 2012). Certificate and associate degree programs are lengthier than workforce development programs, but they facilitate recapture by allowing the student to earn a credential upon successful completion (Koebler, 2012). Recapture is also appropriate for describing mechanisms for increasing the number of teachers in STEM by encouraging nontraditional learners to pursue alternative certification paths (PCAST, 2010; Thomasian, 2011).

Because of the population served, recapture is closely tied to additional STEM processes. Nontraditional students are far more likely to drop out of college because of family, money, job, or health reasons than their traditional peers (Tripp, 2011). Thus, retention quickly becomes an issue for recaptured students. It is generally regarded as cheaper to retain students than it is to recapture them (Stearns, 2011), so a concerted effort and coordination with recapture and retention is critical. Additionally, quality control studies like the Workforce Innovation Fund can assess the impact and success of the recapture processes for workforce development. For example, enhancing the GED test to better prepare students as they enter college is also part of the quality control process. Though the process of recruitment focuses on a younger audience, initiatives for recruitment and recapture can inform each other reciprocally via the process of quality assurance. While recapture and recruitment serve to attract individuals into STEM and retention serves to keep them in STEM, all three processes are often served by the same strategies and interventions (e.g., project-based learning, enrichment programs, supplemental instruction).

Retention

Although the processes of recruitment and recapture address a big issue involving the presence of people engaged in STEM, these initiatives pale in comparison to the efforts needed to keep them in STEM, especially for students from underrepresented groups (Lee & Luykx, 2007; NSF, 2011). *Retention* involves deliberate and systematic approaches aimed at sustaining student interest, achievement, and involvement (NRC, 2011). Because this process is important across the spectrum of ages and grade levels, it includes adults and young children. Retention is an often-discussed and well-recognized process of STEM (Sanders, 2009).

Programs that express a concrete vision for educating underrepresented students aim to bring a broader set of learners into advanced STEM (Means et al., 2008; NRC, 2011), create positive identities (Means et al., 2008), defy prevailing stereotypes about who can succeed, and prepare all students to be literate citizens (PCAST, 2010). Such goals are often organized around curricular changes in the school (Means et al., 2008), extended to the local community (Saint Louis Science Center, Youth Exploring Science Program, 2012), and have a specific focus such as medicine (BOOST Science Program, 2012). Retention can also be addressed by preserving highly qualified mathematics and science teachers through financial incentives, professional development, and leadership opportunities (NRC, 2001, 2010).

Quality Assurance

Retention, recapture, and recruitment can all be optimized through additional processes that provide feedback on their function, influence on each other, and effectiveness. Thus, the primary functions of evaluation are also recognized in the five core process model of STEM. According to Popham (1993), “Systematic educational evaluation consists of a formal appraisal of the quality of educational phenomena” (p. 7). According to Scriven (1991), “The key sense of the term ‘evaluation’ refers to the process of determining the merit, worth, or value of something, or the product of that process” (p. 139). Evaluation occurs through two distinct roles: a formative role that identifies areas where a program, teaching condition, or evaluation can be improved (quality assurance) or a summative role that judges the effectiveness of a program, teaching condition, or evaluation (quality control). Our model recognizes both processes as part of STEM.

Quality assurance refers to the continued and ongoing assessment of the operation of the processes of recruitment, recapture, and retention, including recommendations for improvement (Cuttance, 1994). Quality assurance is a mechanism for monitoring the aforementioned processes and their associated feedback loops with the intent of addressing error prevention (Confrey & Maloney, 2011). In the context of STEM, quality assurance refers to the continued feedback and adjustments to curricula (Confrey & Maloney, 2011), teacher education (Crespo, 2003; National Council for Accreditation of Teacher Education, Blue Ribbon Panel on Clinical Preparation and Partnerships for Improved Student Learning, 2010), and instructional strategies that serve to better recruit, retain, and recapture individuals (Mark, Cooksy, & Trochim, 2009). Professional development represents the primary vehicle for quality assurance of practicing teachers and administrators (Kazemi & Franke, 2003). Quality assurance is also apparent in the evaluation of STEM-focused schools, ensuring their capacity to meet their recruitment and retention goals (Means et al., 2008). The feedback provided by quality assurance often leads researchers and developers to question their assumptions about the goals and operations of the other processes, thus emphasizing the interrelatedness of the system and the utility of feedback loops.

Quality Control

Quality control is a mechanism for ensuring that an output, product, or service conforms to a predetermined specification and often takes the form of program evaluation (Popham, 1993). For STEM, quality control activities are associated with the creation of project deliverables, verification of the deliverables (e.g., curriculum, programs, instructional methods), evaluation to indicate needed corrective responses, and activity focused on process outputs. Issues of quality control include the lackluster performance of U.S. students on international comparisons of science and mathematics achievement (Gonzales et al., 2004). Additionally, the relatively poor performance of U.S. students in mathematics and science correlates to underprepared teachers, ineffective instructional practices of teachers, out of field teachers, difficulty recruiting and retaining qualified teachers, or lack of advanced coursework (NRC, 2001). Current quality control projects seek to identify the types of curricula being used in schools, the impact of interventions on student achievement, the nature of preservice education, and the current teaching workforce as well as the evaluation process itself (Mertens & Hopson, 2006). In short, quality control assesses the capacity of STEM for producing the needed workforce and includes the skills and expectations from students, teachers, principles, and policy makers.

Together, quality assurance and quality control enable the system to evaluate the internal processes as well as the products it creates. In theory, any discrepancies, inefficiencies, or issues

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are addressed through a feedback loop that supports corrective action. For STEM, this implies changes to the processes of recruitment, recapture, and retention. However, critical issues for both quality processes have been identified. These include a lack of well-qualified evaluators, a lack of valid and reliable instruments to measure the outcomes of interventions, a need for new methods of merging data and analyzing large data sets, limited funding for professional development related to evaluation and equity, and diversity issues (Greene, DeStefano, Burgon, & Hall, 2006; Huffman, Lawrenz, Thomas, & Clarkson, 2006; Katzenmeyer & Lawrenz, 2006; Lawrenz & Huffman, 2006). These issues represent focal points for future research and development for improving both the quality-assessment and quality-control processes of STEM.

STEM Is an Integrated System of Processes

Our model recognizes STEM as a fully integrated system in which the processes interact in a reciprocal fashion (i.e., include feedback loops). Thus, the primary process of its focus, as well as the degree to which it involves each of the other processes, can define any STEM initiative. For example, an afterschool STEM program may include activities and strategies like interest clubs (e.g., robotics club or mathematics puzzle club) designed to generate student curiosity regardless of their academic standing. Thus, for those students not engaged with STEM, recruitment is the primary process, and for those active in STEM, retention is the primary process. However, a targeted afterschool program with the primary mission of providing tutoring and homework support would feature retention as the primary process. The process of quality assurance, as a means of formative assessment and improvement, would also serve the activities of both example programs secondarily.

Examples of STEM initiatives vary widely and can include formal educational activities like courses, degree programs, and professional development as well as informal activities such as interest clubs, afterschool programs, and outreach activities. Informal events may be perceived as simply intending to serve the public good and thus not a true STEM initiative (Falk & Dierking, 2010). However, our research suggests that the focus of these events is most likely to be recruitment or recapture due to the overarching goals of building interest, promoting the enterprise and encouraging participation (though retention could also be served). For example, the National Science Teachers Association (NSTA) recognizes that learning in informal environments "promote[s] an appreciation for and interest in the pursuit of science in school and in daily life" (National Science Teachers Association, 2012, para. 1). Thus, we also define these as STEM initiatives and use the process model to interpret their activities and outcomes. Like the disciplines represented in the STEM, the processes of the five core process model are multidimensional and include procedures (e.g., curriculum and instruction, research and development) that consume resources (e.g., time, money, materials) to serve people as the inputs and outputs.

Before discussing our views on the implications of our model and the processes defined within it, it is important to consider the limitations of our research methods and perspective.

Limitations of the Study

This study was limited by a number of factors, including those inherent in the methods of grounded theory, our interpretation and application of the process, as well as the nature of STEM itself. Though we did not stipulate a specific time period, we targeted data sources from the recent past (approximately 20 years) and limited them to descriptions of the situation in the United States. Based upon how STEM is discussed in our profession and society, we assumed that it existed as a construct and purposefully excluded data that focused on proposals or personal opinions for what STEM is or should be. As an inductive process, the sense making involved in the coding of data in grounded theory relies heavily on the diligence and integrity of the research team. In our case, the tension between our use of purposeful sampling and the validity of our grounded theory was a constant presence. Charmaz (2006) describes this as an unresolved issue in using grounded theory. We addressed the tension with a combination of diligence for critiquing our assumptions, seeking feedback on our ideas from knowledgeable others outside of our research team, and a strategy of accounting for any new STEM initiative that we discovered with our model. As a problem of sociopolitical origin, we recognized that the motivation of participating entities was inherently influenced by political agenda, which is often masked in documents or policy. As part of the inductive nature of grounded theory, we identified this masking and, to the extent possible, made explicit the role of politics in the data. To this end, we relied on our use of the constant comparative method as a means of addressing the influence of politics in the substance of our theory, but the degree of success in this effort remains a limitation to our conclusions.

Implications

We view the five core process model as having broad implications across the science, technology, engineering, and mathematics disciplines as well as for each of the processes that define the enterprise. The model's potential emanates from its simplicity and seemingly straightforward connection to existing initiatives. However, the utility is more than simple face validity and affirmation of existing approaches and investments. As a representation of the interrelated processes of a system, it serves as the foundation for the construction of new theory that explicates the relationship among the processes, their connectedness and interdependence, and the relationship between the system and the context that it is situated in. Pragmatically, such a model can lead to new ways to organize institutions and society, to teach and learn, and to view and evaluate our engagement and influence on the system. It affords an interpretation of future innovations in any of the five processes for serving participants from all backgrounds. Thus, the five core process model offers utility for fostering innovation, research, and development at the federal, state, institutional, and classroom level.

Important implications result from our finding that all STEM initiatives serve one primary process as well as additional secondary processes within the model. This finding is independent of whether the intent of an initiative has been explicitly stated or clearly defined. For example, a STEM-focused high school may be serving retention without explicitly stating such. Or, this school may have been fashioned with the primary intent of serving retention but has built structures and programing that principally serves recruitment instead of retention. As such, without a clear articulation of the processes that an initiative intends to serve, the potential for a misalignment exists between the operations of a program and its intended goals. A program intending to serve retention would need to provide structures and programing that specifically target the involvement, performance, and achievement of their target student population. These forms of programming would be very different from that which might be used to serve recruitment, emphasizing enrichment, identity formation, and mentoring.

Situated in the five core process model, we contend that all initiatives should be based upon three primary components: (a) a grounding in empirically supported theoretical models; (b) an explicit conceptual framework that defines the relationship between those theoretical frameworks

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and existing program inputs, operations, assumptions, and external factors; and (c) a logic model or theory of action that makes explicit the reasoning and rationale for how interventions are applied and interact in producing the desired outcomes. Including these components ensures that quality assurance is an explicit component of every STEM initiative. We recognize that this perspective is becoming part of standard practice for some programs and funding agencies, such as those at the U.S. Department of Education, but a more widespread application is needed, including new coursework for graduate students as well as training opportunities for existing professionals.

We would expect that any new STEM initiative would clearly articulate the primary process it anticipates influencing and a logical theory of action—based upon what is known about form and function of that process—for how it intends to do so, including an accounting of any ancillary interrelationships among the processes. From the perspective of quality control, this implies a need for the articulation of a conceptual framework as well as the logic inherent to any proposed innovation. Such a requirement would provide a needed dual focus for serving STEM, improving the initiative's potential for effectiveness as well as the capacity for generating new theory. For example, an informal program for children at a museum has a greater potential for effectiveness if the program were designed to serve recruitment, primarily, instead of retention. Such a program could then focus resources on experiential and enrichment activities that build interest and identity instead of retention services like tutoring or academic support that maintain participation in schools.

The five core process model has implications for initiatives related to each of the included processes. For initiatives related primarily to recruitment, recapture, and retention, quality assurance needs to be a required component. Projects such as these would greatly benefit from a more explicit focus on acquiring and using data to assess and improve their operations. Recruitment activities should be more transparent and accessible (Leggon & Pearson, 2009; Mervis, 2006). Recruitment is often comingled with retention, and although this is may be rationalized as appropriate, the focus of different activities within a program should be delimitated based upon their intent and theoretical grounding so that their differential impact can be assessed. The field would benefit from documented effects for specific strategies and programmatic structures that target enrichment, identity formation, and mentoring—in particular, the effectiveness of these strategies for traditionally underrepresented populations of students. All forms of strategies and program structures should be assessed for quality control and, when feasible, appropriately scaled.

Financial constraints impede certain populations of students from participating in STEM because the cost of pursuing a postsecondary degree is often greater than other majors (Schultz et al., 2011). This issue could be addressed with new interventions that target retention and recapture of underrepresented students. Fast Forward New Mexico, a program providing free Internet training for residents who do not otherwise have access to or cannot use Internet resources, is an example of such an intervention. The program aims to provide digital literacy skills and awareness of the power of online resources to those who participate. Although these skills do not necessarily point learners toward a particular job, the project relies on a "documented link between broadband deployment, jobs, and output growth" (Fast Forward New Mexico, 2012, p. 1). In addition, diversity needs to be assessed continually as part of the quality control process. Without explicitly emphasizing diversity as a dimension of quality control, we run the risk of over emphasizing volume and throughput (i.e., sheer numbers) as the primary predictor of recruitment, recapture and retention. Initiatives for recruitment and recapture should be coupled to efforts for retention. Generating student interest is only the first step; sustaining this interest while also building knowledge and skills is challenging and can quickly become an issue (Hidi & Renninger, 2006). In turn, this implies that retention initiatives should be more tightly coupled to efforts for quality assurance, acquiring and using data to improve the likelihood of achieving their goals and outcomes.

We need to better understand how to recapture adults of all demographics back into the system, the motivations and aspirations of recaptured students, and models for appropriate, supportive educational experiences for recaptured students. Because people displaced from the formal educational system represent the largest available cache of human capitol (Tripp, 2011), recapture and retention are processes in need of research and development. Based upon their maturity, life situation, and prospective lack of success with the disciplines (Baldwin, 2009), this population of students is expected to need alternative forms of education and tight coupling of retention to recapture (Lamos, Simon, Waits, Fulton, & Bird, 2010). Further, a thoughtful application of quality assurance to a concerted effort and coordination between recapture and retention can be mutually informative for all processes.

Project evaluation for all STEM initiatives needs to include an explicit blend of quality assurance and quality control components. For example, projects need to be designed to include meaningful assessments throughout their lifespan that offer the potential for redesign. To this end, design-based research with iterative cycles of design-evaluation-redesign offers tremendous potential (Confrey, 2006; Kelly, Lesh, & Baek, 2008). Evaluation that views STEM as a system and considers the relationships among the processes would be most informative. With a systems perspective, efficiency, cost–benefit analysis, and sustainability are all appropriate metrics for assessing quality. In addition, quality assurance and control need to assess the financial impact of funded initiatives on the outputs of recruitment, recapture, and retention. All initiatives must successfully draw in and retain a volume of diverse students. Any initiative that does not account for underrepresented students runs the risk of resulting in a decrease in the overall volume of students or an unpredicted change in the type of students pursuing a credential, thus having the opposite of the intended effect.

Conclusion

Using grounded theory methods to synthesize and interpret the federal perspective, this study defined STEM as a model that includes five core processes that interact to support the system in achieving its goal of producing a qualified future workforce. Defining STEM in terms of a process model affords an opportunity to advance research and development by moving beyond the rhetoric about what STEM should be to first recognizing it as a formal, logical system that is intended to bring about an important outcome—improving the quantity and quality of the future workforce. Such a model has implications for advancing the overall goals of STEM as well as further research and development on the components of the model itself.

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APPENDIX

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Learning From Student Projects in Logic Design

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Abstract

As an introductory course, Logic Design is geared towards familiarizing students with concepts, design, and practical use of digital circuits and systems. Part of the course requirement is for students to form teams and work together to conceptualize and design a digital system that meets an identified need for existing conditions or anticipated futuristic technology. This paper presents student approach to the process of need identification, conceptualization, design, and optimization of a digital system in a term project setting. In conclusion, we discuss lessons learned from student logic design, creativity, and aspirations.

Keywords: Computer science; Engineering; Logic design; Technology

The objective of any engineering program is for students to gain the ability to transfer classroom learning to practice for which they will be required to apply knowledge towards problem solving. *Transfer* is a degree of understanding beyond memorization; it indicates the ability to process information and integrate knowledge in new contexts (Mativo & Smith, 2011). Students need to master original information and transfer the knowledge to new applications (Mativo & Smith, 2011; Goldman et al., 2008). Fundamentals of Logic Design is an introductory course at the sophomore level. Topics include digital system and information, combinational logic circuits and design, sequential logic circuits and design, optimization and tradeoffs in design, and physical implementation of design. Course goals include learning logic design concepts and application to solving realistic problems. In this introductory course, students had time to learn the basics of logic design through lecture, assignments, demonstrations, and exams. A term project served as the capstone for students to demonstrate their mastery of the course work.

Method

Dr. Mativo was instructor of the course and collaborated with Dr. Huang to investigate student learning through projects in Logic Design. At the beginning of the course, students were introduced to the fundamentals of logic design, such as gates, truth tables, and logic circuits. State graphs and machines were introduced and used for larger designs with multiple inputs and multiple outputs. In the last few weeks of the course, programmable devices were introduced and used in discussing memory basics. The term project was assigned to students during their 6th week of a 15-week semester. Together with the students, we stablished a timeline for term project component completion. These components included identifying the need, conceptualizing and design, optimizing, and presentation. Students were to complete their projects by the end of the semester.

Students were to design a circuit that would serve as a solution to an existing problem or offer a new invention. The engineering design process (EDP), or a variation thereof, was to be followed in this problem-solving exercise. The EDP that students were given included the following steps: establishing the need, developing a problem statement, searching for existing solutions, developing alternative solutions, deciding on a solution, and proposing that solution. Student teams of three to four self-selected members were formed, and teams worked towards a successful completion of their chosen term project.

Teams

Self-selected teams were formed to provide students with an environment in which to use their acquired knowledge in creative problem-solving ventures with the aim of addressing Accreditation Board for Engineering and Technology (ABET, 2011) Criterion 3: Student Outcomes a, c, e, g, j, and k:

> (a) an ability to apply knowledge of mathematics, science and engineering . . .
>
> (c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability . . .
>
> (e) an ability to identify, formulate, and solve engineering problems . . .
>
> (g) an ability to communicate effectively (3g1 orally, 3g2 written) . . .
>
> (j) a knowledge of contemporary issues
>
> (k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice. (p. 3)

Expectations

Each team was expected to create an invention that addressed an existing need or an anticipated need of the future. The team was to conceptualize and strengthen their initial concept by searching through resources such as literature and patent reviews to establish whether solutions to their identified needs and concepts had already been solved or to gather information that would be helpful in their designs. In the design phase, students were expected to develop a state graph that would help them generate a state table and a Karnaugh map (or maps) as a way to optimize the design. Finally, they were to create a digital circuit and identify hardware that would allow for building a virtual model or a physical model on a breadboard.

In the following sections, three examples of student team self-selected projects, identified as Teams 1, 2, and 3, are presented. It should be noted that we preferred to keep student artwork and writing as original as possible; therefore, any sketch and typographical errors have been preserved. A discussion and conclusion follow these sections.

Team 1: Traffic Light Control and Sensor

Need

The need was to design a traffic light control device that induces forced vehicle stopping. The team's statement was as follows:

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To develop a traffic light control system that allows signals to be transmitted by traffic light and received by an approaching vehicle 20 meters before the light is red. The purpose of the device is to enable the vehicle to come to a stop without running a red light. Once sensors receive signal from traffic light control machine, sensors will press brake automatically for drivers. Current traffic light's countdown system has not prevented drivers from car accidents happened nearby intersection because some drivers are using their phones or doing other things while they are driving. These behaviors make them not able to see traffic light or misunderstand about traffic light so that they might get car accidents by red-running violations. Therefore, we need to develop and modify the current traffic light control system and machine to become better device for drivers' safety.

Conceptualization and Design

Search for information. Through a search of the literature and the patent office, the team found no existing devices or mechanisms similar to the proposed idea. Therefore, the team's approach to finding a solution, as shown below, included developing a problem state, state graph and table, Karnaugh map, and circuit (see Figures 1–3 and Table 1).

Problem State:

(i) When the car key is inserted and car gear shift is on D, then X is activated.

(ii) When car gear shift is on P, then X is deactivated.

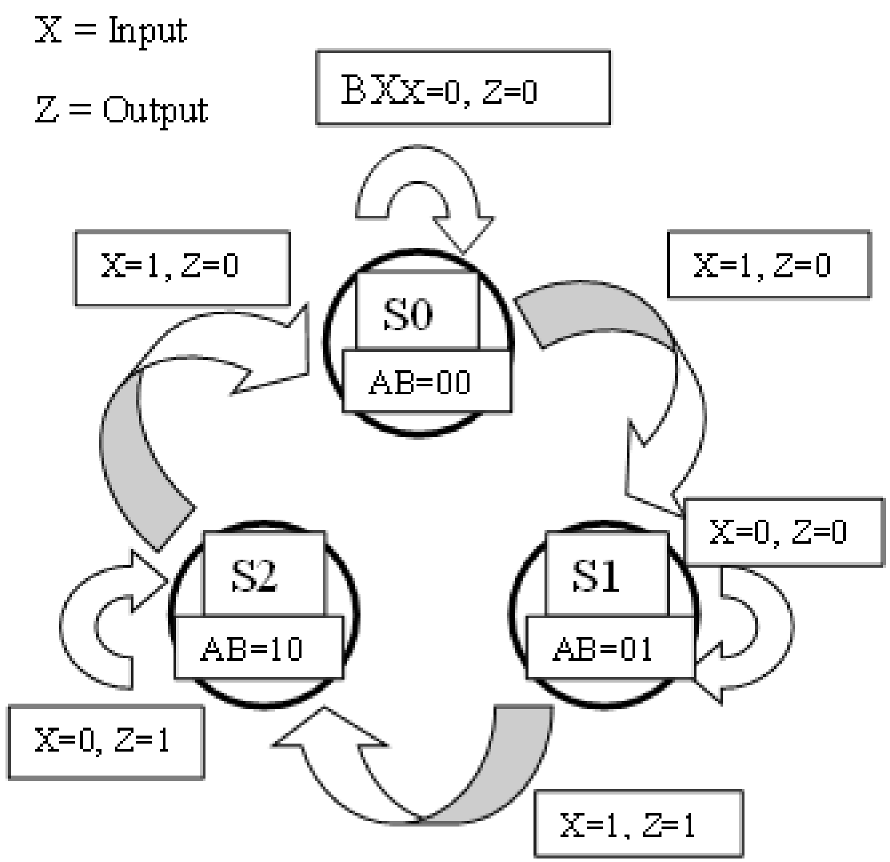
(iii) When the car is approached about 20 meters from traffic control machine, the traffic light control system sends signal to sensor in the car and the car sensor senses a traffic light turning red, then Z is activated.

(iv) The automatic control system overrides mechanical braking system and slow down car to stop in

(v) As long as the light is red, then automatic control system is deployed, otherwise it is deactivated.

Table 1
State Table for Traffic Light Control Circuit

Present State		Input	Next State		Output
A	B	X	A+	B+	Z
0	0	0	0	0	0
0	0	1	0	1	0
0	1	0	0	1	0
0	1	1	1	0	1
1	0	0	1	0	1
1	0	1	0	0	0
1	1	X	X	X	0
1	1	X	X	X	0



1. S0, X=0, Z=0; Reset, which means that if car key is not inserted, then sensor is deactivated.
2. X=1, Z=0; When driver puts gear shift on D, sensor is activated.
3. S1, X=0, Z=0; When driver puts gear shift back on P, then sensor is deactivated.
4. X=1, Z=1; When car approaches about 20 meters from traffic light control machine at the intersection, traffic light control system sends signal to sensor in the car so that sensor received signal with time for how long is left for traffic light to change from green to red, and then braking system is activated.
5. S2, X=0, Z=1; Since sensor knows when traffic light will change, it does not have to be keep activated while traffic light is changing green to red because braking system takes over to press brake automatically for a car to stop completely.
6. X=1, Z=0; Once traffic light is red, the sensor is activated again. When sensor got signal that traffic light is changed back to green, then the output braking system is deactivated.

Figure 1. State graph for traffic light control. The box at right shows the stages in the state graph, starting with the top of the graph and moving clockwise

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$$Z = A\bar{B}\bar{X} + \bar{A}BX$$

A \ BX	00	01	11	10
0	0	0	1	0
1	1	0	0	0

Figure 2. K-map for Z.

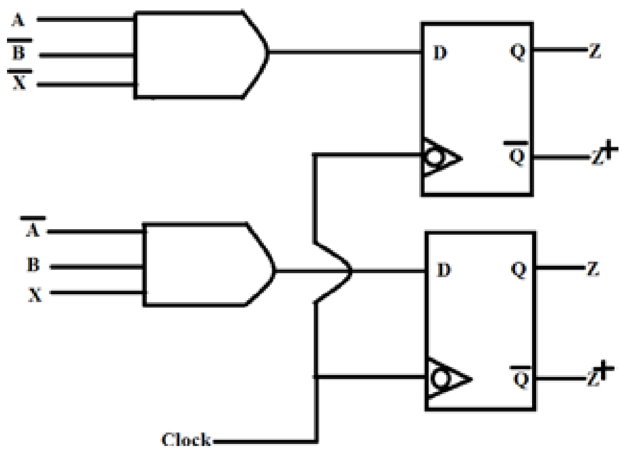

Figure 3. Circuit design for traffic light control circuit.

The optimization process involved developing a Karnaugh map and then algebraically manipulating the results to arrive at the best solution for each case.

Hardware. The hardware proposed for this design would include 2 AND Gates (3 inputs each) and 2 D Flip Flops

Student Summary

> The new traffic light control system and sensor are pursued because these machines will protect people's safety and save many things such as money and time from car accidents. Especially, if there is only traffic light control's countdown system and no sensor inside of car, then drivers have a choice to make a decision so that there is a chance for them to get car accidents from making wrong decision when they are about to cross intersection. Since there is the sensor which presses brake automatically when traffic light is about to change, all cars will stop at the moment of the traffic light is changing, so the car accidents would not be happened at the intersection anymore. Therefore, people need to modify current traffic light control system and develop sensor to put all cars to prevent car accidents to protect people's safety and save many things such as money and time.

Team 2: A Shower Temperature Alarm

Need

The need was to develop a shower alarm system. The team's statement was as follows:

> Knowing instantly when shower water has reached the correct temperature would save time, money, and would be good for the environment. The need for this device stems from a problem shared by many when it comes to taking showers. When the average person starts their shower routine, the first thing they do is turn on the shower. After that, they have to wait for a variable amount of time while the water warms up to their desired temperature; no one wants to get in a cold shower, but no one wants to sit and wait for it to warm up, either—they could be doing other things. The proposed product will need a way to measure water temperature. It will also need a way to know & store the user's desired temperature, a mechanism for alerting them, and a way for the user to interface with the device.

Conceptualization and Design

Search for information. A search for information revealed that the problem is currently not being solved by any external devices, so the team did not have much to go off of or modify. The device design would be able to sound an alarm if the temperature went over a certain threshold (specified in the software). The alarm would stop if the button was held down for 2 seconds. The temperature would be measured by a sensor in the shower head.

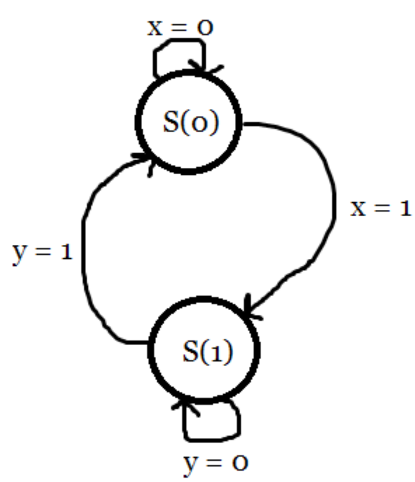

Figure 4. State graph for shower temperature alarm.

In this state graph (Figure 4), S_0 represents the alarm-off state. In this state, the device will be constantly reading the temperature of the shower. S_1 represents the alarm-on state in which the alarm will be beeping. State variable x is HIGH when temperature is above the threshold and LOW otherwise. State variable y is HIGH when the button has been held down for 2 seconds, and LOW otherwise.

Breadboard. Team 2 built and tested their alarm system based on their state graph. Figures 5 and 6 show their alarm-thermostat circuit design.

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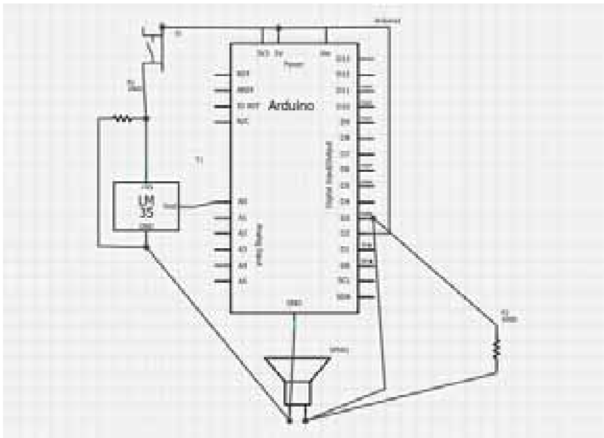

Figure 5. Circuit.

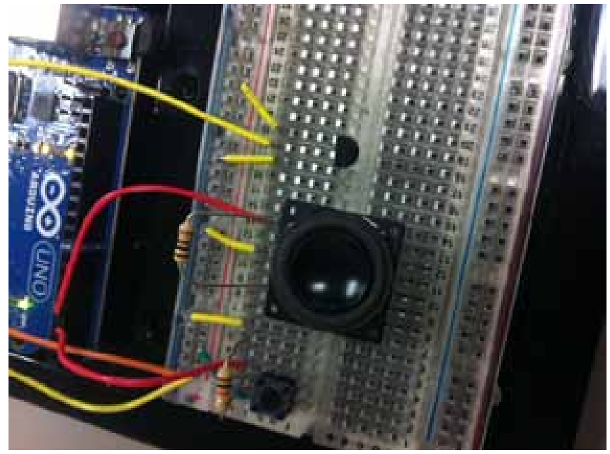

Figure 6. Breadboard.

Student Summary

> With the knowledge we have now, we can definitely manufacture and implement this product as stated above. In the future, we should be able to augment the software and hardware to allow for an LCD screen, multiple users on the same device, and multiple settings for even more personalization. As it is now, our problem should be solved—a quick, safe, cheap, and easy way to always know when the shower reaches your favorite temperature. No more wasted water, no more wasted time, and no more wasted money!

Team 3: Intelligent Ejector Seat in Cars

Need

The need was to design a logic system that will trigger occupant ejection from a car. The team's statement was:

> The slack design of seat-belts allows free movement can prove hazardous (Dickinson, T. 2001). Our intelligent car seat design will remove you from the car if you are in a collision that meets the requirements in order for a chance of seat-belt injury to occur. By implementing this system we hope to decrease causality rate for specific speeds (between 55 and 70 mph).

Conceptualization and Design

Search of information. No devices like this exist in automobiles. The team developed a state graph (Figure 7) and a state table (Table 3), and they optimized it by using Karnaugh maps (Figure 8).

Table 2
Binary Representation of a 3, 4, 1, 6, 2, 5 Car Ejector System Design

Event	A	B	C
Key in ignition	0	1	1
Vehicle in motion	1	0	0
Speed tracking	0	0	1
Impact sensed	1	1	0
Activate car seat eject	0	1	0
Eject car seat	1	0	1

The binary representation above (see Table 2) was developed to show that any sequential or arbitrary design could work for our case. In our case we used an arbitrary state.

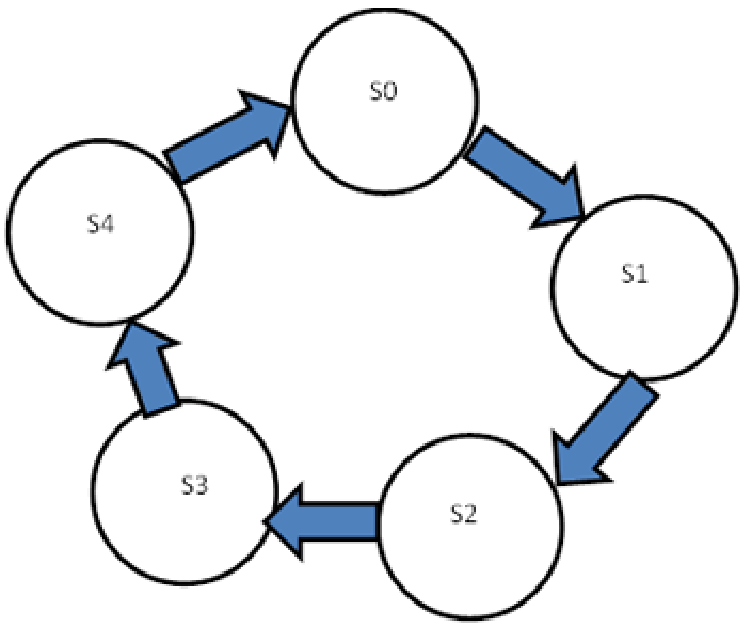

Figure 7. State graph to activate car seat eject

Table 3
State Table of Car Seat Ejector Design

Present State			Next State		
A	B	C	A^+	B^+	C^+
0	0	0	d	d	d
0	0	1	1	1	0
0	1	0	1	0	1
0	1	1	1	0	0
1	0	0	0	0	1
1	0	1	0	1	1
1	1	0	0	1	0
1	1	1	d	d	d

Note. “d” represents don’t care.

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$A^{+} = \bar{A}$

BC

A

d	1	1	1
0	0	d	0

$B^{+} = \bar{B}C + AB$

BC

A

d	1	0	0
0	1	d	1

$C^{+} = A\bar{B} + \bar{A}\bar{C}$

BC

A

d	0	0	1
1	1	d	0

Figure 8. K-maps for A^{+}, B^{+}, and C^{+}.

Hardware. The hardware proposed for this design would include 3 D Flip Flops, 2 two input OR gates, and 4 two input AND gates.

Student Summary

> The proposed design could be implement to the preexisting technology found on most modern cars. The car possesses four different cameras which cover all angles of the car and have the ability to measure relative speed of objects around the car as well as determine how close an object is. The technology of airbag deployment will be used in the car seat deployment. The design is for an open car without a roof. There are more considerations on the car ejection relative to card design and could be implemented in future cars.

Other Projects

The project titles not presented in this paper include: DawGone Night Bobber, Automatic Door and Air Conditioning System, and Security Camera Design for special applications. The DawGone Night Bobber provided better fishing rod and line for the night fisher by adding a sensor to the mechanism to indicate whether a large fish or small fish had been caught. Additionally, a light was placed at the bobber to attract fish. The Automatic Door and Air Conditioning System integrated both systems for the prevention of bugs that fly into restaurants. A customer approaching the automatic door would trigger its sensor causing the air conditioning system to turn on acting as an air curtain at the door and effectively keeping bugs away. The Security Camera Design project was to designed an advanced image storage system that would enable stored images to be compared to new ones and would notify the operator if there was an anomaly in any of the target areas.

Discussion and Conclusion

Although this was an introductory course, it showed that students were able to understand logic design concepts and transfer this knowledge to problem solving activities. The time to learn and understand course material was relatively short; however, we believe the time period was sufficient for the introductory course. Lessons learned from this experience include:

1. Students were able to connect course relevance to learning logic design basics from number theory, defining the problem accurately, logic gates, truth tables, digital circuits, state graphs, and programmable devices. By using common logic examples such as calculators, timers, and seat belt illustrations, students were able to associate course material to product design. A sample specific example given in class was an aircraft lavatory where three lavatories were available to the passengers. Each lavatory was equipped with a sensor which would register "1" when occupied and "0" when not occupied. Students were able to develop equations that would allow this to happen. From the equation, they sketched a circuit and were able to see how logic works itself into a physical phenomenon. Further, from their course experience, they were able to transfer that knowledge to providing solutions to problems as exemplified from the three examples presented in this paper. Their ability to use the engineering design method to develop digital circuit that could be incorporate to an existing circuit or as a standalone product is evidence of ability to transfer.
2. Creativity—Students were creative in conceptualizing futuristic needs such as traffic project, shower temperature alarm, intelligent ejector car seat, and more. Authors learned that given time, students armed with logic design can become innovators at a very early stage in their education preparation.
3. Gained confidence—Students were able to present their work in class for not only show and tell but respond to criticisms from their fellow classmates. Some teams realized that their designs were inadequate and needed further attention, while others were ready to develop their ideas into products. A good example work that needed further attention is figure 7 which depicts state graph that lacks an S5 state. Students were able to recognize that during their presentation and were crafty to adjust the figure description, which did not actually solve the problem.
4. A need to provide students with virtual Boolean logic builder and simulator LOGICLY to provide hands-on experiences to students in this course.

Our overall observation was that the term project was an effective way to aid in teaching because it provided a feedback loop that is open to both students and instructor. First, students were required to provide the best possible solution by determining the smallest sum of products having minimal minterms and variables. They learned this process would help them to not only determine the hardware cost and reduced space need but also optimize operation by reducing delays from solutions with unnecessarily more hardware. This activity helped in meeting ABET's Criterion 3 student outcomes for a, c, and e. Second, at presentation time, students learned to provide scientific/engineering reasons on why they thought their design were better suited to provide solutions for the identified problem. This activity helped satisfy ABET's Criterion 3 student outcomes for g, j, and k. We observed that introductory courses could benefit students by adding a component of a "capstone" type term project into their courses. This would challenge the student to think beyond just doing well in exams. Further, we believe a rubric to determine

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the degree of student achieving in each of the criterion would be helpful in understanding student learning and devise ways to design course for highest attainment.

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Expanding Earth Science in STEM: A Model

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Abstract

Despite the national call for STEM preparation, there is still a need to foster student interest in STEM at an early age. Although stakeholders have begun to develop STEM curricula at the elementary level, many of these focus on single disciplinary content and often have an emphasis on physical science. Efforts must be made to develop STEM curriculum that is truly integrated and adequately represents NGSS grade-level learning. This may require the use of interdisciplinary teams to improve integrated STEM programs. Projects like the covered wagon mini greenhouse can be used to strengthen student interest in STEM and encourage students to understand and practice the design process while engaging in earth science instruction.

Keywords: Earth science, Integration, NGSS, STEM

National Call for STEM Preparation

Despite increased national attention to the need for more K–12 curriculum and instruction centered on science, technology, engineering, and mathematics (STEM), students who graduate from high school with sufficient skills in these areas seem to be in short supply. In 2012, Uttal and Cohen stated that “there is little doubt that the United States faces a serious, and growing, challenge to develop and educate enough citizens to perform jobs that demand skill in . . . [the STEM] domains” (p. 148). Similarly, Rockland et al. (2010) noted that

> [The STEM fields] are in desperate need of more qualified workers, yet not enough students are pursuing studies in . . . [STEM] that would prepare them for technical careers. Unfortunately, many students have no interest in STEM careers . . . because they are not exposed to topics in these fields during their K-12 studies. (p. 53)

In 2010, the National Science Board reported that the American and global economies had changed substantially over the previous decade with an increased importance on science, technology, and innovation. In that same year, President Obama stated that “strengthening STEM education is vital to preparing our students to compete in the 21st century economy” (The White House, Office of the Press Secretary, 2010, para. 2). Most researchers and governmental authorities agree that adding higher numbers of STEM trained professionals to the workforce would vastly increase the global competitiveness of the United States (Tsupros, Kohler, & Hallinen, 2009, Atkinson & Mayo, 2010; National Science Board, 2010).

> The increase in professional workers in . . . [STEM] fields in the United States has seen steady growth over the past decade, but lags behind the dramatic growth of our . . . global

> competitors in developed countries (National Science Board, 2010). (DeJarnette, 2012, p. 77)

Additionally, DeJarnette (2012) reports that

> Results on the PISA [Program for International Student Assessment] and TIMSS [Trends in International Mathematics and Science Study] international studies . . . have shown that American youth fall behind other developed countries in countries in their abilities in science and math (Russell, Hancock & McCullogh, 2007; Russell, 1999). (p. 78)

The perceived need to increase the economic output of the United States and the academic performance of American students has resulted in pressure to develop STEM initiatives in public schools.

These pressures have resulted in a number of STEM curriculum and instruction programs such as Project Lead the Way (PLTW), Engineering by Design (EdB), Engineering is Elementary (EiE), and many other programs. As a result, the importance of providing earlier exposure to STEM learning for students in grades K–12 has increasingly come to light (Bagiati, Yoon, Evangelou, & Ngambeki, 2010; Bybee, & Fuchs, 2006). Most of these programs have been designed to impact students in middle and high school, "but there has been little change in the elementary curricula to support these growing trends" (DeJarnette, 2012, p. 77). Bencze (2010) suggested that "although there is considerable academic and official curricular support for promoting student-directed, open-ended science inquiry and technological design projects in schools, the reality is that they rarely occur" (p. 58). Hoachlander and Yanofsky (2011) noted that

> There are few more crucial initiatives . . . [in school reform] than increasing student proficiency in . . . [STEM]. Yet in too many schools, STEM is still mostly science and mathematics, taught separately with little or no attention to technology and engineering. Where connections do get made to technology and engineering, too often they happen through a hodgepodge of disconnected projects that lack coherence or strong grounding in content standards and student performance objectives. (p. 60–61)

Educational leaders and public and private organizations around the nation are beginning to offer STEM curriculum programs for K–12 students. These programs range from instilling increased rigor into single discipline subjects within the STEM acronym to a variety of STEM inspired activities.

> But generally speaking, it usually includes the replacement of traditional lecture-based teaching strategies with more inquiry and project-based approaches. To some, it only becomes STEM when integrating science, technology, engineering, and math curricula that more closely parallels the work of a real-life scientist or engineer. To others, STEM is the push for graduating more students in the science, technology, engineering, and mathematics fields. (Breiner, Harkness, Johnson, & Koehler, 2012, p. 3)

For the purposes of this discussion, we will limit our foci to those programs that strive to integrate the STEM disciplines. As Moore (1903) suggested more than a century ago, students need to see the connections between different subjects, and teachers need to be intimately familiar with the relationships within and between the STEM disciplines.

In response to the push of STEM assimilation into classrooms, teachers are seeking curriculum models and lessons that can be integrated into their instruction. For many of these teachers, especially those in elementary settings, this is their first exposure to technology and engineering (Murphy & Mancini-Samuelson, 2012). This unfamiliarity can be a barrier for teachers and school

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administrators looking to implement STEM curricula.

Effective STEM education entails the purposeful integration of all four areas (Bybee, 2010; Roberts, 2012; Stohlmann, Moore, & Roehrig, 2012). Due to the increased attention on STEM education, proposed curricula and teaching resources are emerging to assist educators in K–12 classrooms. These curricula are often developed in the form of lesson plans, instructional resources, and student activities. A content analysis conducted by the researchers of existing STEM curricula for elementary education shows anecdotal evidence that earth science content is insufficiently represented, and the prominence of the letter *S* in STEM education is often associated with the physical sciences. Many STEM lessons include properties of matter, motion, gravity, energy, and simple machines.

STEM and the New Science Standards

Elementary teachers are sometimes challenged to find ways to include science in their curriculum, particularly during the years prior to science achievement testing. Those wishing to integrate STEM learning look for ways to combine science and engineering with other, usually tested, subject matter such as mathematics and literacy. To address the need for greater emphasis on connections between and among the STEM disciplines, science educators have recently updated the existing *National Science Education Standards* (NSES, 1996) to include a greater emphasis on engineering. Drawing from the *Standards for Technological Literacy* (STL; International Technology Education Association [ITEA], 2007); the *Next Generation Science Standards* (NGSS; NGSS Lead States, 2013) include engineering, which is intricately linked to the practice and understanding of science. NGSS advocates integrating eight distinct Science and Engineering Practices in the classroom. These include:

1. Asking questions [for science] and defining problems [for engineering]
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using mathematics and computational thinking
6. Constructing explanations [for science] and designing solutions [for engineering]
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information. (NGSS Lead States, 2013, p. xx)

In the NGSS, a Science and Engineering Practice (SEP) is combined with a Disciplinary Core Idea (DCI) and a Crosscutting Concept (CC), and the resulting standard is expressed as a Performance Expectation (PE) that demonstrates a student's level of understanding of relationships among science and engineering practices, science core content ideas, and broader connections to overarching science concepts (NGSS Lead States, 2013). Each performance expectation establishes what students will be able to do at the end of instruction and would realistically require several individual lessons that build toward the goals of the PE. Examples of performance expectations related to this project include:

3-ESS3-1. Make a claim about the merit of a design solution that reduces the impacts of a weather-related hazard. (p. 33)

This PE requires that students are Engaging in Argument from Evidence about the merit of their design (SEP) and relating Cause and Effect (CC) to reduce the impact of weather-related Natural Hazards (DCI).

> **4-PS3-4.** Apply scientific ideas to design, test, and refine a device that converts energy from one form to another. (p. 35)

This PE requires that students are Constructing Explanations and Designing Solutions (SEP) and understand Conservation of Energy and Energy Transfer (DCI) related to Energy and Matter (CC).

> **5-ESS2-1.** Develop a model using an example to describe ways the geosphere, biosphere, hydrosphere, and/or atmosphere interact. (p. 50)

This PE requires that students are Developing and Using Models (SEP) and that they understand the components of Earth Materials and Systems (DCI) and the interactions among components of Systems and System Models (CC).

Finally, performance expectations provide excellent opportunities for teachers to make numerous connections to Common Core State Standards for mathematics (CCSS-M; National Governors Association Center for Best Practices [NGA] & Council of Chief State School Officers [CCSSO], 2010b) and English language arts (CCSS-ELA; NGA & CCSSO, 2010a). Students are encouraged to use mathematics in applied situations rather than the more theoretical approach used in most K–12 classrooms. STEM integration requires students to measure, graph, and interpret results. Literacy, both oral and written, is supported through the reading and writing of informational text and through the oral communication of ideas. The NGSS-SEP, STL, and CCSS-M work in combination to allow students to understand how all STEM disciplines are related and build upon one another.

The NGSS are comprised of four core topics: earth and space science, life science, physical science, and "engineering, technology, and applications of science" (NGSS Lead States, 2013, p. xvi). Earth and space science are broken down into three progressions: Earth's Place in the Universe, Earth's Systems, and Earth and Human Activity. Each of these earth science progressions can provide an excellent context for STEM learning. The following design project was developed to illustrate how a STEM lesson might highlight earth science themes such as ecosystems, plants, animals, and soil properties.

The Covered Wagon Greenhouse Project

The design and construction of a greenhouse integrates all disciplines of STEM education, while emphasizing Earth science, an integral part of the NGSS for elementary students. The Covered Wagon Greenhouse project includes Earth and physical sciences, technology, engineering design concepts, and mathematics calculations. This project also allows for further extension activities, community involvement, or cocurricular collaboration. Students are guided to build their own mini greenhouse for use during the duration of the school year to grow small plants, vegetables, or flowers. Using predetermined materials, student teams design and construct a greenhouse that provides continuous learning opportunities throughout the school year. Students work collaboratively in engineering design teams to conduct ideation, problem solving, and make needed adjustments as they work to complete the project. This project promotes creativity, teamwork, troubleshooting, and exploration.

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Getting Started

Similar to many lesson plans, this project can be modified to fit the needs and resources of any classroom. The following guidelines and standards are designed for third through fifth grade classrooms. There are six overall steps that are essential for students to construct their own learning and to develop a deeper understanding of STEM concepts within the project.

Step 1. Students conduct research to learn about greenhouses, how they work, their purpose, what they are made of, and other relevant goals that may situate this project in the existing classroom. There are a multitude of Internet resources and videos that can assist the students and teacher to learn more about greenhouses and how to build them. The shape and structure of a covered wagon may provide students with a starting point on the structural design of the greenhouse.

Step 2. After the teacher introduces students to the purpose of the project and the basics of greenhouses use and design, the students work in teams to make a list of materials they think would be needed to build their own greenhouse. It is essential that the teacher facilitate these discussions and help guide students' ideas to an appropriate scale and type of construction that they will use in their design. Students will undoubtedly come up with many ideas beyond those of the teacher. This may provide excellent opportunities for the teacher to foster engaging discussions about the best possible materials to use and how the materials will be used for construction. It may also provide an opportunity to bring in an expert from the construction trades. It is important that the teacher encourage students to be creative and have the freedom to explore their own ideas regarding design and construction.

Step 3. Students devise a plan for constructing the most effective mini greenhouse their group can come up with. This planning phase can be done together as a class or in small groups. Younger students may need more assistance and facilitation than older students. It is important that students understand the purpose of the greenhouse, what will be planted in it, available materials, and exactly how to engineer the best design. This is an excellent opportunity for sketching and planning for the overall dimensions of the design.

Step 4. Students create a budget for their mini greenhouse and brainstorm ideas for funding the purchase of materials and supplies. Students should use spreadsheet software to devise their own budget with possible sources of support as one component. Ideas for support include donations from local garden shops, dry cleaners (hangers), or recycling centers (plastic clothing bags). Once the students have created a materials and budget list, they can write letters to local businesses or organizations to request donations or support for their mini greenhouse projects.

Step 5. Once all materials are obtained, students begin construction of their mini greenhouses according to their plan from Step 3. This is where problem solving and troubleshooting come into play. With guidance from the teacher, students should be able to follow directions according to the group or class plan of construction. The materials presented below are only suggestions. Students may discover ideas for other appropriate building materials during the design process.

Step 6. Once students have completed their greenhouse construction, it is important that they present their designs to an audience. Members of the community, parents, and students from other grades may be asked to come, providing an authentic audience to whom the students will present their findings and completed projects.

Suggested Materials (per engineering design team)

- 1 rectangular planter that is large enough for the intended purpose (additionally, students

may design and build their own planter from recycled materials, see Figures 1–3)
- 7–10 wire hangers (or other sturdy but flexible wire)
- 10 ft smaller, more flexible wire (floral wire)
- Wire cutters
- Gloves for handling wire
- Clear plastic to cover greenhouse (could use large clear plastic bags)
- Enough soil to fill planter
- Seeds

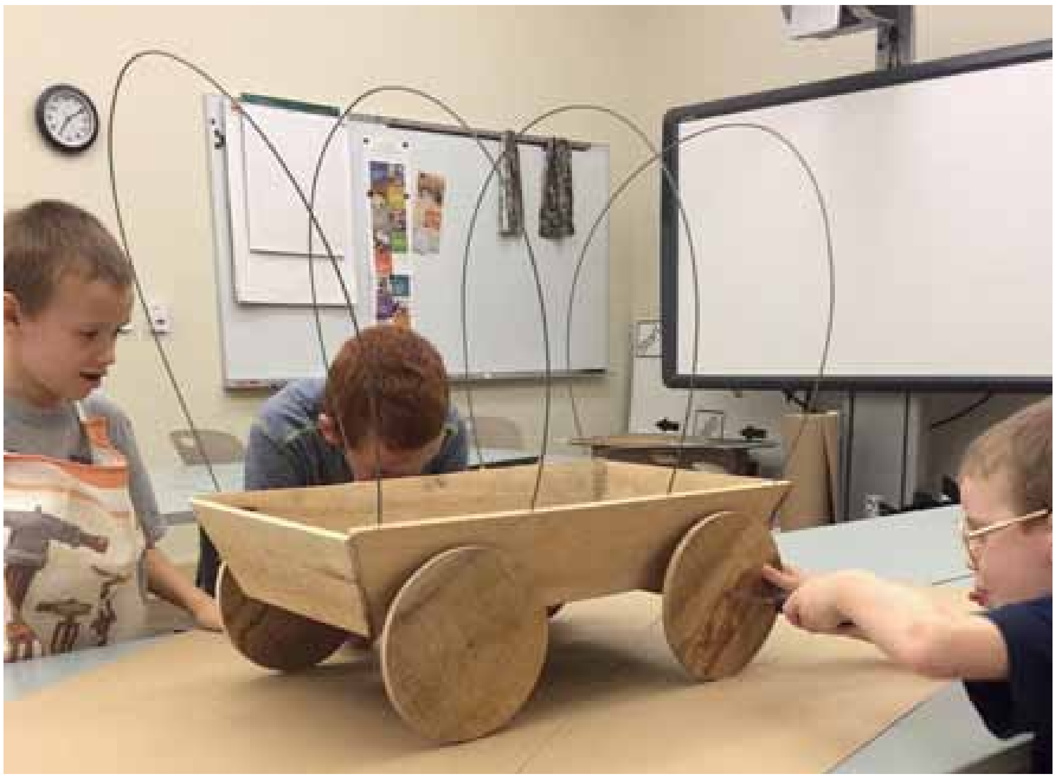

Figure 1. Elementary students assemble their own planter from recycled materials.

Project Instructions

The following steps can be used to construct the covered wagon mini greenhouse using the suggested materials list provided above.

1. Fill planter with potting soil about one inch from the top.
2. Plant seeds in soil (this can also be done after the greenhouse is constructed).
3. Take wire hangers apart and straighten them.
4. Measure length of planter, and determine how many wire hangers will be needed for truss supports. For a 20 in planter, we recommend putting a wire hanger every 2–3 inches.
5. Measure and mark on planter where bent wire hangers will be stuck in the soil to support the plastic covering.

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Figure 2. Elementary students add potting soil to planter.

6. Bend the wire hangers in the shape of a horseshoe, and poke both ends into the soil right up against the sides of the planter. This will make a rainbow-shape over the planter that resembles the top of a covered wagon.

   Note: This may require multiple students working together to hold the wires in place because they will be unstable until wired together. Depending on the height of the planter, the ends of the wire hangers may need to be secured to the sides of the planter for stability. This can be done by drilling holes in the side of the planter and wiring the truss wires to the sides of the planter.

7. Once 3–4 of the wire hangers have been placed, use thinner wire to connect them together and add support for the top. This will begin to strengthen the arc and hold the wire hangers in place. Repeat until all wires have been used and the top begins to resemble the top of a covered wagon. This will serve as the support for the plastic covering.

8. Now the two ends of the greenhouse will need to be made. The two ends will serve as doors to access the plants inside and will also allow heat to escape when necessary. Door frames and hinges will need to be constructed out of more wire. There are many ways of doing this, but the doors will need to be sturdy enough to be opened and shut frequently.
9. The door frames should be made from the thicker hanger wire, but the grid-like support on the inside could be done with floral wire. Students will need to measure and configure doors that hinge from the top and can be propped open.
10. Once the "covered wagon" top and doors are strong and stable, it is time to cover them with clear plastic. Depending on the plastic used, there may be different ways of completing this step most effectively.

Figure 3. Elementary students add plastic cover to the greenhouse in preparation for planting.

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11. Students must measure and cut proportionate sizes of plastic to fit on the greenhouse cover. One solid piece would cover the main arch, but plastic on the doors must cover all cracks when the doors are shut. Students must problem solve to determine how to do that as well as keep the doors accessible. This is another way that students must be creative and come up with the best way to make sure the plastic is tightly sealed when the doors are shut. This could be done with Velcro strips on the outsides of the doors, small snaps for extra plastic to cover around the doors, or any other way of ensuring a closed container when the doors are shut. This will keep the warm air in and the cool air out.
12. The final step in the covered wagon mini greenhouse project is determining how to extend the project beyond planning and construction. Maintenance of the greenhouse and the plants inside is a crucial aspect of this project, but students and teachers should also devise a plan for extending collaboration and further learning activities using the mini greenhouse. Possible ideas include inviting garden specialists in from the community to speak about other possible garden projects, discussing what can be grown in a greenhouse year round and the importance of self-sustainment and nutrition. Other suggestions include conducting a plant life cycle lesson observing the growth of plants, studying the greenhouse effect in an atmosphere lesson, or developing a project, titled Build a Better Greenhouse, using what they learned from their first design.

Connection to Standards

This project, including extension activities, offers an eclectic array of valuable learning experiences for students at any grade level. Standards addressed by this project may vary, depending on targeted concepts or how in-depth teachers are able to develop the project. Table 1 lists the national standards in mathematics, English language arts, science, and technological literacy that could potentially be addressed by this project and further extension activities.

- **Common Core State Standards: Math, Grades 3–5 (NGA & CCSSO, 2010b)**
    - Within this project, students have the opportunity to perform tasks that align with the Common Core State Standards (CCSS) regarding measurement of volume and length, geometry concepts, and calculating formulas. Students will calculate the amount of soil needed to fill the planter, measure where the wire braces will need to be placed, calculate the plane area of plastic needed to cover the greenhouse, and measure the perimeter for accurate construction of doors for the greenhouse.
- **Common Core State Standards: English Language Arts, Grades 3–5 (NGA & CCSSO, 2010a)**
    - Additional writing could be incorporated into this project, but the existing format does align with English Language Arts CCSS in grades 3–5. Students will be making step-by-step instructions for construction of the mini greenhouse, which involves writing with a specific task and purpose in mind. Organization of thoughts and explanation are essential to this project. Students will be researching using online or print materials, reading for understanding, and using the information they find to make predictions and plans for designing and building their greenhouses.

Table 1

National Standards Addressed by the Covered Wagon Greenhouse Project

National Standards	Grade Level	Individual Standards/Performance Expectations Addressed
Next Generation Science Standards (Performance Expectations) (NGSS Lead States, 2013)	3	**3-ESS2-2.** Obtain and combine information to describe climates in different regions of the world. **3-ESS3-1.** Make a claim about the merit of a design solution that reduces the impacts of a weather-related hazard.
	4	**4-LS1-1.** Construct an argument that plants and animals have internal and external structures that function to support survival, growth, behavior, and reproduction. **4-PS3-4.** Apply scientific ideas to design, test, and refine a device that converts energy from one form to another. **4-PS3-2.** Make observations to provide evidence that energy can be transferred from place to place by sound, light, heat, and electric currents.
	5	**5-ESS2-1.** Develop a model using an example to describe ways the geosphere, biosphere, hydrosphere, and/or atmosphere interact.
Standards for Technological Literacy (ITEA, 2007)	3–5	**Standard 5.** Students will develop an understanding of the effects of technology on the environment. **Standard 8.** Students will develop an understanding of the attributes of design. **Standard 9.** Students will develop an understanding of engineering design. **Standard 10.** Students will develop an understanding of the role of troubleshooting, research and development, invention and innovation, and experimentation in problem solving. **Standard 11.** Students will develop the abilities to apply the design process. **Standard 12.** Students will develop the abilities to use and maintain technological products and systems. **Standard 15.** Students will develop an understanding of and be able to select and use agricultural and related biotechnologies. **Standard 17.** Students will develop an understanding of and be able to select and use information and communication technologies.
Common Core State Standards: Math (NGA & CCSSO, 2010b)	3	**CCSS.Math.Content.3.MD.A.2** Measure and estimate liquid volumes and masses of objects using standard units of grams (g), kilograms (kg), and liters (l).1 Add, subtract, multiply, or divide to solve one-step word problems involving masses or volumes that are given in the same units, e.g., by using drawings (such as a beaker with a measurement scale) to represent the problem. **CCSS.Math.Content.3.MD.B.4** Generate measurement data by measuring lengths using rulers marked with halves and fourths of an inch. Show the data by making a line plot, where the horizontal scale is marked off in appropriate units— whole numbers, halves, or quarters. **CCSS.Math.Content.3.MD.C.5** Recognize area as an attribute of plane figures and understand concepts of area measurement.
	4	**CCSS.Math.Content.4.MD.A.1** Know relative sizes of measurement units within one system of units including km, m, cm; kg, g; lb, oz.; l, ml; hr, min, sec. Within a single system of measurement, express measurements in a larger unit in terms of a smaller unit. Record measurement equivalents in a two-column table. **CCSS.Math.Content.4.MD.A.3** Apply the area and perimeter formulas for rectangles in real world and mathematical problems. **CCSS.Math.Content.4.G.A.1** Draw points, lines, line segments, rays, angles (right, acute, obtuse), and perpendicular and parallel lines. Identify these in two-dimensional figures.
	5	**CCSS.Math.Content.5.MD.C.5b** Apply the formulas $V = l \times w \times h$ and $V = b \times h$ for rectangular prisms to find volumes of right rectangular prisms with whole-number edge lengths in the context of solving real world and mathematical problems.
Common Core State Standards: English Language Arts (NGA & CCSSO, 2010a)	3	**CCSS.ELA-Literacy.W.3.4** With guidance and support from adults, produce writing in which the development and organization are appropriate to task and purpose. **CCSS.ELA-Literacy.RI.3.5** Use text features and search tools (e.g., key words, sidebars, hyperlinks) to locate information relevant to a given topic efficiently. **CCSS.ELA-Literacy.RI.3.7** Use information gained from illustrations (e.g., maps, photographs) and the words in a text to demonstrate understanding of the text (e.g., where, when, why, and how key events occur).
	4	**CCSS.ELA-Literacy.W.4.8** Recall relevant information from experiences or gather relevant information from print and digital sources; take notes and categorize information, and provide a list of sources. **CCSS.ELA-Literacy.W.4.5** With guidance and support from peers and adults, develop and strengthen writing as needed by planning, revising, and editing. **CCSS.ELA-Literacy.RI.4.7** Interpret information presented visually, orally, or quantitatively (e.g., in charts, graphs, diagrams, time lines, animations, or interactive elements on Web pages) and explain how the information contributes to an understanding of the text in which it appears.
	5	**CCSS.ELA-Literacy.W.5.4** Produce clear and coherent writing in which the development and organization are appropriate to task, purpose, and audience. **CCSS.ELA-Literacy.RI.5.7** Draw on information from multiple print or digital sources, demonstrating the ability to locate an answer to a question quickly or to solve a problem efficiently. **CCSS.ELA-Literacy.RI.5.9** Integrate information from several texts on the same topic in order to write or speak about the subject knowledgeably.

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National Standards	Grade Level	Individual Standards Addressed
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	4	**4-LS1-1.** Construct an argument that plants and animals have internal and external structures that function to support survival, growth, behavior, and reproduction. **4-ESS2-1.** Make observations and/or measurements to provide evidence of the effects of weathering or the rate of erosion by water, ice, wind, or vegetation.
	5	**5-ESS2-1.** Develop a model using an example to describe ways the geosphere, biosphere, hydrosphere, and/or atmosphere interact. **5-ESS1-1.** Support an argument that the apparent brightness of the sun and stars is due to their relative distances from Earth.
Standards for Technological Literacy (ITEA, 2007)	**3–5**	**Standard 5.** Students will develop an understanding of the effects of technology on the environment. **Standard 8.** Students will develop an understanding of the attributes of design. **Standard 9.** Students will develop an understanding of engineering design. **Standard 10.** Students will develop an understanding of the role of troubleshooting, research and development, invention and innovation, and experimentation in problem solving. **Standard 11.** Students will develop the abilities to apply the design process. **Standard 12.** Students will develop the abilities to use and maintain technological products and systems. **Standard 15.** Students will develop an understanding of and be able to select and use agricultural and related biotechnologies. **Standard 17.** Students will develop an understanding of and be able to select and use information and communication technologies.
Common Core State Standards: Math (NGA & CCSSO, 2010b)	**3**	**CCSS.Math.Content.3.MD.A.2** Measure and estimate liquid volumes and masses of objects using standard units of grams (g), kilograms (kg), and liters (l).1 Add, subtract, multiply, or divide to solve one-step word problems involving masses or volumes that are given in the same units, e.g., by using drawings (such as a beaker with a measurement scale) to represent the problem. **CCSS.Math.Content.3.MD.B.4** Generate measurement data by measuring lengths using rulers marked with halves and fourths of an inch. Show the data by making a line plot, where the horizontal scale is marked off in appropriate units— whole numbers, halves, or quarters. **CCSS.Math.Content.3.MD.C.5** Recognize area as an attribute of plane figures and understand concepts of area measurement.
	4	**CCSS.Math.Content.4.MD.A.1** Know relative sizes of measurement units within one system of units including km, m, cm; kg, g; lb, oz.; l, ml; hr, min, sec. Within a single system of measurement, express measurements in a larger unit in terms of a smaller unit. Record measurement equivalents in a two-column table. **CCSS.Math.Content.4.MD.A.3** Apply the area and perimeter formulas for rectangles in real world and mathematical problems. **CCSS.Math.Content.4.G.A.1** Draw points, lines, line segments, rays, angles (right, acute, obtuse), and perpendicular and parallel lines. Identify these in two-dimensional figures.
	5	**CCSS.Math.Content.5.MD.C.5b** Apply the formulas $V = l \times w \times h$ and $V = b \times h$ for rectangular prisms to find volumes of right rectangular prisms with whole-number edge lengths in the context of solving real world and mathematical problems.
Common Core State Standards: English Language Arts (NGA & CCSSO, 2010a)	**3**	**CCSS.ELA-Literacy.W.3.4** With guidance and support from adults, produce writing in which the development and organization are appropriate to task and purpose. **CCSS.ELA-Literacy.RI.3.5** Use text features and search tools (e.g., key words, sidebars, hyperlinks) to locate information relevant to a given topic efficiently. **CCSS.ELA-Literacy.RI.3.7** Use information gained from illustrations (e.g., maps, photographs) and the words in a text to demonstrate understanding of the text (e.g., where, when, why, and how key events occur).
	4	**CCSS.ELA-Literacy.W.4.8** Recall relevant information from experiences or gather relevant information from print and digital sources; take notes and categorize information, and provide a list of sources. **CCSS.ELA-Literacy.W.4.5** With guidance and support from peers and adults, develop and strengthen writing as needed by planning, revising, and editing. **CCSS.ELA-Literacy.RI.4.7** Interpret information presented visually, orally, or quantitatively (e.g., in charts, graphs, diagrams, time lines, animations, or interactive elements on Web pages) and explain how the information contributes to an understanding of the text in which it appears.
	5	**CCSS.ELA-Literacy.W.5.4** Produce clear and coherent writing in which the development and organization are appropriate to task, purpose, and audience. **CCSS.ELA-Literacy.RI.5.7** Draw on information from multiple print or digital sources, demonstrating the ability to locate an answer to a question quickly or to solve a problem efficiently. **CCSS.ELA-Literacy.RI.5.9** Integrate information from several texts on the same topic in order to write or speak about the subject knowledgeably.

- **Next Generation Science Standards, Grades 3–5 (NGSS Lead States, 2013)**
  - Multiple science content areas are covered in this project with an emphasis on earth science. Students will learn about and explore the impact that different climates can have on plants and learn about plant structures that support survival. In building up to this project and from researching the purpose of a greenhouse, students will also apply their knowledge of the effects of weather and atmospheric conditions. Students will engage in discussion about why there are changes of season and the need for greenhouses in the colder months. Teachers can facilitate deeper understanding of this content throughout the project as needed.
- **ITEA Standards for Technological Literacy, Grades 3–5 (ITEA, 2007)**
  - Students will be exposed to several aspects of technology and engineering in this project, including the design and engineering process. Students will be problem solving and troubleshooting within their groups or as a class and will be connecting concepts of technology to earth science and the environment. At the beginning of the project, students will be using technological devices to research about the project and to acquire material that will inform the rest of the process of design and implementation.

For the Students

Providing learning guides such as the planning sheet below will help students successfully navigate through this project. Predetermined note sheets and lesson guides will offer some structure and concrete approaches to the more abstract portions of this project comprising the design process. For example, the project planning sheet (see Figure 4) represents a guide that students may use for brainstorming, listing materials, sketching, and performing calculations. It may be important that students see examples of existing greenhouses (and covered wagons).

<table>
<tr><td colspan="6">Project Planning
Name:____ Date: ____________________</td></tr>
<tr><td>What did I learn from my research?</td><td colspan="5"></td></tr>
<tr><td>What materials will we need?</td><td colspan="5"></td></tr>
<tr><td rowspan="3">Where can we get materials?</td><td>Item</td><td colspan="2">Business/Organization</td><td colspan="2">Contact Information</td></tr>
<tr><td></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>What steps will it take to build our greenhouse?</td><td><u>Step 1</u></td><td><u>Step 2</u></td><td><u>Step 3</u></td><td><u>Step 4</u></td><td><u>Step 5</u></td></tr>
<tr><td>What will our greenhouse look like when we are done?</td><td colspan="5"></td></tr>
</table>

Figure 4. Project Planning Sheet

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Considerations for Teachers

The researchers assisted students in the development of the pilot version of this project. During the pilot, students designed and used previously gathered materials. Students could create their own covered wagon greenhouse in 4 to 6 hours, depending on age and skill level; however, this is just the beginning because students learn how to use the greenhouse and modify it for its intended purposes. One important facet of a STEM project is that students guide their own learning. Students must uncover each step of the project from the ground up, including researching, brainstorming, planning, budgeting, and executing. It is common for teachers to order a commercially available kit for building a greenhouse; however, using a kit does not allow students to fully engage in the design process. Students should begin with researching the purpose of greenhouses, how and why they work, materials, and the structural elements of covered wagons. The role of the teacher is essential in facilitating each step of the design process during the project. Some steps in the project may need to be performed by the teacher for safety reasons, depending on the age level of students.

There can be many variations of this greenhouse project that offer the same quality of learning experiences for students. Depending on resources, budget, number of students, grade level, and other factors, variations may be critical for completion of this project. Teachers may prefer to give students a few guidelines and let them be the explorers and designers. It is crucial that teachers be creative and resourceful and that they encourage the students to do the same. Ultimately, students should understand the entire purpose and process of building a greenhouse at the conclusion of the project.

Summary and Call to Action

Furthering efforts to engage K–12 students in integrated STEM education are necessary to the future of our nation and the sustained strength and growth of our nation's labor force. Although the need to expose students to and get them interested in STEM content and careers at an early age has been noted by professionals, unfortunately, many students do not have the opportunity to study STEM subjects until they reach secondary schools. Additionally, many of the initiatives to develop and implement STEM into schools are focused on single disciplinary content. It is important that students are exposed to STEM learning through an interdisciplinary approach that makes connections to the real-world use and application of STEM content knowledge.

Stakeholders have responded by developing programs that focus primarily on physical science. Efforts must be made to develop STEM curriculum that is truly integrated and adequately represents NGSS grade-level learning. This may require the use of interdisciplinary teams to improve integrated STEM programs. Projects like the covered wagon mini greenhouse can be used to strengthen student interest in STEM and to encourage students to understand and practice the design process while engaging in earth science instruction.

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Engineering Design: The Great Integrator

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Abstract

There is much support in the research literature and in the standards for the integration of engineering into science education, particularly the problem solving approach of engineering design. Engineering design is most often represented through design-based learning. However, teachers often do not have a clear definition of engineering design, appropriate models for teaching students, or the knowledge and experience to develop integrative learning activities. The purpose of this article is to examine definitions of engineering design and how it can be utilized to create a transdisciplinary approach to education to advance all students' general STEM literacy skills and 21st century cognitive competencies. Suggestions for educators who incorporate engineering design into their instruction will also be presented.

Keywords: Engineering design; STEM; Integration; Teaching and learning

Background

Perusing the *Framework for K–12 Science Education* (National Research Council [NRC], 2012) and the *Next Generation Science Standards* (NGSS; NGSS Lead States, 2013), one quickly recognizes the degree of support and rationale for integrating engineering into science education. According to Hosni (2013),

> The meaningful integration of engineering practices in the NGSS will promote critical thinking, provide new levels of relevancy to motivate students to learn science content, make engineering and engineering careers more accessible to all students, and prepare the next generation to solve global problems facing humanity." (p. 1)

However, engineering alone does not produce such outcomes. Specifically, *engineering design*, a form of problem solving (Visser, 2009), affords students the opportunity to develop 21st century cognitive competencies, engage in authentic engineering practices, and integrate science and mathematics concepts.

Engineering design is most often represented through design-based learning (DBL), a pedagogical approach that Grubbs (2013) states has already been adopted across multiple science, technology, engineering, and mathematics (STEM) disciplines (e.g., Crismond & Adams, 2012;

Doppelt, Mehalik, Schunn, Silk, & Krysinksi, 2008; Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004; Jacobson & Lehrer, 2000; Kolodner et al., 2003). However, as deviations of DBL have emerged with varying utilitarian perspectives, teachers often do not have a clear definition of engineering design, appropriate models for teaching students, or the knowledge and experience to develop integrative learning activities. The purpose of this article is to examine definitions of engineering design and how it can be utilized to create a transdisciplinary approach to education to advance all students' general STEM literacy skills and 21st century cognitive competencies. Suggestions for educators who incorporate engineering design into their instruction will also be presented.

Engineering and Engineering Design

The notion of integrating engineering into science education is not a novel idea. Originating in *Science for All Americans* (American Association for the Advancement of Science [AAAS], 1990) and *Benchmarks for Science Literacy* (AAAS, 1993), assimilating both disciplines was attributed to the belief that they were inseparable beyond formal education (NRC, 2009). Scientific knowledge informs the engineering process, whereas new scientific discoveries are fueled by technology created through engineering design. As the *Framework for K–12 Science Education* (NRC, 2012) indicates, engineering has not received the same level of attention in science curricula as traditional science disciplines. Therefore, the NGSS (NGSS Lead States, 2013) were developed with a commitment to further integrate engineering into science education by treating engineering design as tantamount to scientific inquiry. Blending scientific and engineering practices into the structure of science education and including engineering design as one of the disciplinary core ideas are fundamental themes of the NGSS. However, the infusion of these practices also presents pedagogical implications for nonengineering educators. In his critique of the 2013 NGSS draft, Buchanan (2013) argued that "the draft presents engineering and science as synonymous terms, rather than the interrelated yet distinctly different fields that they are" (p. 1). Although science and engineering are "interrelated," it is important for students to understand that they are "distinctly different fields."

Engineering

Operationally defining engineering and the role it plays in education provides a framework for nonengineering educators to move forward. The National Research Council (2009) defines engineering as the process of designing the human-made world, which is composed of technological developments such as buildings, roadways, airplanes, and televisions. Engineers use the process of designing to modify the natural world to meet human needs and desires by creating solutions to life's problems using the scientific knowledge obtained through scientific inquiry (NRC, 2009). In addition to this definition, two important distinctions also need to be considered: the purpose of including engineering in K–12 education and what design actually entails. From a progressivist standpoint, the purpose of engineering in K–12 education is to immerse students in a setting in which they can all benefit from thinking like engineers. This view is modeled by technology and engineering education, a school subject that identifies engineering as a profession closely related to its instructional practices and strives to prepare all students to solve modern societal problems through engineering design (Asunda & Hill, 2007; ITEEA, 2002; NRC, 2009). "Exposure to technological concepts and hands-on, design-related activities in the elementary and

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secondary grades are the most likely ways to help children acquire kinds of knowledge, ways of thinking and acting, and capabilities consistent with technological literacy" (National Research Council, 2002, p. 57). This view is explicitly distinguished by the International Technology and Engineering Education Association (ITEEA) who distinguishes teaching "little 'e'" over "Big 'E'" engineering. Whereas "Big 'E'" engineering focuses on the noun, or career oriented purpose, "little 'e'" engineering focuses on the verb, preparing all students to think like engineers and developing students to fully participate in a 21st century society. Although the authors of this paper also differentiate between the two different outcomes, they also give moderate attention to both goals becuase this argument is not a concern of the chemistry, biology, or physics classrooms. The authors believe that engineering should be taught in its true sense and not reduced to terms that are not true of the engineering profession. Teaching in this manner can benefit all students, regardless of their career path, but will still provide them the skills and knowledge to pursue an engineering degree. This is similar to the different science disciplines; for example, students in a biology classroom are not all going to become biologists.

Although design is considered to be the distinguishing activity of engineers (Dym, Agogino, Eris, Frey, & Leifer, 2005) and is the focus of various engineering curricula (Jain & Sobek, 2003), the term is used loosely. Various terms and definitions have been presented, encompassing multiple fields from the fine arts to engineering and from technological design to engineering design. Choices about which term to use, such as *informed design* (Burghardt & Hacker, 2004), or what characterizes engineering design (Merrill, Custer, Daugherty, Westrick, & Zeng, 2008) can drastically affect subsequent instructional approaches, cognitive demands placed upon students, and expected learning outcomes.

Characterizing Engineering Design

The capacity design has to increase student learning and foster 21st century cognitive competencies begins with understanding its purpose. Asunda and Hill (2007) define design very simply: "Design refers to the process of devising something. It is a creative, iterative and often open-ended process of conceiving and developing components, systems, and processes" (p. 26). The *Standards for Technological Literacy* (2007), which was originally published in 2000, identifies design as a basic element in learning about technology, which requires both conceptual and procedural knowledge, and describes it as a core problem-solving process of technological development. The *Standards for Technological Literacy* (2007) makes the claim that learning to design provides students with a set of abilities that will serve them throughout their lives. As Friesen, Taylor, and Britton (2005) explain, design is a creative, iterative, and open-ended process for devising a solution to a problem. Defined in this way, design follows a trial-and-error approach, which is often identified as technological design. Although, this approach is suitable at many levels, engineering design follows a more explicit and intentional path.

Contrasting technological design, *engineering design*, is "'design under constraint'" (Wulf, 1998, para. 4). Constraints such as time, capital, safety, materials, tools, energy, environmental regulations, ergonomics, and manufacturability direct individuals in effectively and efficiently solving problems in a practical manner leading to the production of the most viable solution. Employing engineering design can broadly be described as the ability to take a problem, specify its constraints, establish the corresponding criteria, and adhere to the criteria and constraints to enact a design process for creating a practical solution to the problem. The authors of this article view engineering design as a *directed* form of cognition and more than just mere problem solving, which can be *unintentional*. Engineering design includes the practice of optimizing solutions using a variety of tools for modeling and analysis. Because of the inclusion of the elements of optimization, modeling, and analysis in the design process, engineering design has now replaced the older concept of technological problem solving (NGSS Lead States, 2013). As the NGSS (NGSS Lead States, 2013) assert, providing students a foundation in engineering design allows them to better engage in and aspire to solve the major societal and environmental challenges that they will face in the decades ahead.

Achieving Integration Through Engineering Design

The traditional or "siloed" approach to teaching STEM subjects has been a major contributor to the lack of student interest in STEM activities and careers as well as a reason behind the mediocre performance of U.S. students on international assessments (NRC, 2009). Recently, engineering design has been associated with various efforts to teach STEM subjects in an integrated manner (National Academy of Engineering [NAE] & National Research Council [NRC], 2014). Therefore, it may be viewed as a critical component or link for developing integrative STEM curricula. Integrative STEM education (I-STEM ED) can be defined as the "'application of technological/ engineering design based pedagogical approaches to intentionally teach content and practices of science and mathematics education concurrently with content and practices of technology/ engineering education . . . .' (Wells & Ernst, 2012). (as adapted from Sanders & Wells program documents 2006-10)." (Virginia Polytechnic Institute and State University, 2015, para. 2). Engineering design problems not only provide a clear link between science and engineering but also allow connections to other school subjects.

The integrative capability of engineering design is evident in the engineering design process, which is a problem-solving method that engineers use—along with knowledge from science and mathematics—to solve technological challenges (NRC, 2009). The National Research Council (2009) believes increasing the visibility of engineering and technology in STEM education is vital for the interconnections of teaching and learning. This is supported by research indicating integration can improve student scholarship and engagement (Baker, Krause, Yasar, Roberts, & Kurpius, 2005; Silk, Schunn, & Cary, 2009). The outcome of integrative teaching by using engineering design is transdisciplinary learning through an authentic context that promoting student STEM literacy and readiness for STEM-related employment, which contributes to their own economic success as well as the nation's (NAE & NRC, 2014; NRC, 2009).

Promoters of integrative pedagogical approaches emphasize how professions related to the different academic subjects have transformed into transdisciplinary ventures. This transformation has created a need for integrative STEM practices that focus on real-world contexts and student questions related to local or global issues (NAE & NRC, 2014). *Transdisciplinary learning* has been defined as the organization of curriculum and instruction around student questions that are related to societal problems; concepts and skills are developed through authentic contexts, and students are exposed to STEM-related careers (Drake & Burns, 2004; Maryland Department of Education, 2013). This transdisciplinary learning can be accomplished by using engineering design problem-based tasks that involve authentic situations. For example, Strimel (2014a) used the issue of hydraulic fracturing in the shale gas extraction process as the central context for creating lessons across various subjects. In these lessons, he allows students to question the issue of handling the

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expended and contaminated hydraulic fracturing water used during the shale gas extraction process and engages them in identifying or defining a problem to solve related to this issue. This type of practice requires knowledge and skills from various disciplines in order to enact the engineering design process, devising solutions to a real issue and developing new knowledge through scientific inquiry while also being exposed to potential STEM-related careers.

Engineering-Design-Based Learning

Both engineering-design-based learning and problem-based learning attempt to engage students in addressing complex issues in authentic contexts. A problem-based learning environment centered on engineering design problems can provide students with the opportunity to learn and apply a variety of STEM concepts while also constructing new knowledge. Engineering-design-based learning should be an experiential strategy in a science educator's toolbox for encouraging active learning through engaging students in solving authentic, ill-structured problems that require the integration of theory and practice. This is not to be confused with *project-based learning*, a teacher-structured approach designed for students to learn specific concepts or to demonstrate current competencies. Conversely, *problem-based learning* is a teacher-facilitated strategy constructed around authentic, ill-structured problems that allows for a student's voice in learning and generating new knowledge in order to demonstrate their capabilities without the explicit need to construct a product or intentionality of integration.

The authors believe that there can be two approaches for engineering design activities. The first is to simply engage students in learning through simple, unrealistic, hands-on activities that provide a context for new learning opportunities. This type of activity engages students in the lesson by completing an "engineering" challenge, yet provides few learning opportunities because it is not authentic in nature. Examples of these activities are often found in K–12 engineering curricula (i.e., build the tallest tower using marshmallows and spaghetti). These types of engineering challenge activities lack authenticity and do not actually provide the skills needed to design and create viable solutions to a problem. However, with teacher instruction, these simple activities can be used as a context for teaching essential topics. A second approach is to provide students with opportunities to use industry quality materials, tools, and resources to solve an authentic problem requiring the application of knowledge, leading to the development of new knowledge. The second approach can be more conducive to I-STEM ED but is sometimes viewed as challenging to teach (Ribeiro, 2011), whereas the first approach is easier to achieve because it can be done with little preparation and only uses inexpensive, unrealistic materials. But, with the first approach, how much learning occurs? Can a student learn the concepts involved in designing a new structure using marshmallows and spaghetti to build the tallest tower? Can teachers really say they are teaching engineering if students are not optimizing designs using realistic materials for modeling and analysis? It is important that educators provide students with an authentic experience and move past activities that solely require materials such as popsicle sticks, index cards, hot glue, and tape (Grubbs, 2014). However, using the proper materials, tools, and resources can be challenging and expensive. These challenges are why the authors recommend working collaboratively with a school district's engineering and technology teacher to establish a true authentic and integrative learning experience for students.

Replicating Engineering Design Problems

The *Framework for K–12 Science Education* (NRC, 2012) states all K–12 students should be provided with opportunities to solve engineering design problems carry out scientific investigations. Signifying the importance of understanding the specifics of an engineering design problem, Jonassen (2011) believes that problems vary in three aspects: *context*, *complexity*, and *structure*. Engineering design problems are considered to naturally be the most complex and least structured problems. The key element here can be the degree of structure within a problem statement, varying from well-structured to ill-structured. An example of a well-structured problem may be found in a physics textbook in the form of a word problem. Such a problem requires students to enact a set of steps or to use a formula to arrive at the correct solution. Conversely, ill-structured problems have no standard process for arriving at a solution and have few implications for a correct final solution. A study conducted in the engineering workplace by Jonassen, Strobel, and Lee (2006) identified engineering problems as "ill-structured and complex because they possess conflicting goals, multiple solution methods, non-engineering success standards, non-engineering constraints, unanticipated problems, distributed knowledge, collaborative activity systems, the importance of experience, and multiple forms of problem representation" (p. 139) and often consist of "aggregates of well-structured problems" (p. 142). Problems of this nature can be found in engineering-design-based classroom activities. A classroom enabling students to attempt to solve ill-structured engineering design problems can provide learners with an authentic learning experience while promoting development of essential 21st century skills.

Engineering design problems themselves can also vary in the extent to which they are structured based on how they are constrained or unconstrained (Hutchison & McKenna, 2008). Fully constrained engineering design problems, such as the problem presented in Figure 1, are well-structured problems; they provide a defined problem statement and a complete list of solution criteria and constraints.

> Your environmental engineering team must design and build an inexpensive, easy to use, easy to assemble, durable, and low maintenance device to improve the quality of water using low cost, readily available materials to quickly remove containments from water.

Figure 1. Well-structured engineering design problem. This problem statement includes a defined problem and portrays what successful solutions will consist of.

Conversely, unconstrained, ill-structured engineering design problems provide a situation involving a global or local issue requiring students to define their own problem and establish their own criteria and constraints based on research, thus, giving them a voice in what they are learning and doing. Strimel (2014b) provides an example of an ill-structured engineering-design-based lesson centered on the global concern of mitigating the devastating effects of a major earthquake on a developing nation. This lesson does not provide students with a defined problem but with a situation involving key concepts related to the course subject in which students can identify their own problem to solve. Dependent upon the experience and capability of students to solve engineering design problems, teachers may initially immerse students in well-structured problems until engineering design strategies can be developed. Teachers may then transition students towards more ill-structured design problems once the students are more capable of solving them.

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Developing Integrative Lessons Using Engineering Design

Developing a truly I-STEM ED transdisciplinary lesson requires an intentional and strategic effort when using engineering-design-based learning to meet necessary education outcomes. The lesson should first be based upon desired course content standards and objectives. The required content standards and objectives can then be used to guide the identification of a relevant local issue (such as hydraulic fracturing near Pittsburgh, Pennsylvania or water contamination in Charleston, West Virginia) or a global issue (such as genetically engineered foods, natural disasters, climate change, or sustainable development) to explore. These issues can then provide situations for students to identify, define, and validate an engineering design problem to solve. Investigating these types of issues also require scientific inquiry both to develop knowledge needed for a solution and to evaluate the success of the solution itself. Once again, it is important to remember that these issues should be anchored in content standards.

$$Z = A\bar{B}\bar{X} + \bar{A}BX$$

A \ BX	00	01	11	10
0	0	0	1	0
1	1	0	0	0

Figure 2. I-STEM ED transdisciplinary lesson planning process.

Lesson Title	
Time:	
Lesson Overview/ Purpose: *Provides a paragraph stating the overall big idea of the lesson and its intended outcome.*	
Core Content Standards: *Lists the specific core standards required for the course.*	
Global or Local Issue: *Describes an overarching issue or challenge related to the core content standards.*	
STEM Standards: *Lists and describes the connections between the overarching issue or challenge with other standards and objective from various school subjects.*	
Student Outcomes: *Provides the measurable student outcomes for the lesson's standards and objectives.*	
Enduring Understandings: *Lists the key takeaway items from the lessons that transcend the lesson itself and are applicable to various situations.*	
Driving Question: *Provides a question for driving student investigations about the overarching issue or challenge that will guide inquiry and problem identification and definition.*	
Career Connections: *Lists and describes specific career relationships that are to be incorporated throughout the lesson.*	
Engineering Design & Scientific Inquiry Based Lesson	
Engage: Sets the context for what the students will be learning in the lesson, as well as gaining their interest in the topic.	*Should involve some type of hands-on problem-solving activity that engages students in the lesson and provides a context for the lessons overarching challenge or issue.*
Explore: Enables students to build their own knowledge on the topic while making connection to their prior conceptual and procedural knowledge.	*Should involve some type of investigation activity that will enable students to identify and define a specific problem to solve from the overarching challenge or issue.*
Explain: Summarizes new and prior knowledge while addressing any misconceptions the students may hold.	*Should involve a student-centered discussion of the overarching issue or challenge, as well as the student-defined problems with a purpose of identifying the key concepts needed to be learned to begin developing solutions.*
Engineer: Requires students to apply their knowledge and skills using the engineering design process to identify a problem and to develop a solution.	*Should require students to enact the engineering design process to create a model or prototype to solve an authentic problem using realistic tools and materials.*
Evaluate: Allows a student to evaluate hers or his own learning and skill development in a manner that enables them to take the necessary steps to master the lesson content and concepts.	*Should require students to reflect on the effectiveness of their developed solution and their level of achieving the intended lesson outcomes.*

Figure 3. Engineering design problem-based lesson format

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Next, a teacher can select standards and skills from other school subjects considered necessary for investigating the identified issue and developing potential solutions to a student defined engineering design problem. When students are solving these problems they should be required to use and apply the proper and industry-quality materials, resources, and technological tools. Strimel (2014b) explains that this is where a team of teachers is beneficial because if one teacher is uncomfortable with the integration of a certain standards, concepts, or technological tools, the other teachers, especially an engineering or technology teacher, can assist. Then, the teacher can develop the specific student outcomes of the lesson that describe the transferable knowledge and skills that they should acquire throughout the lesson. The outcomes may be written as a short statement, beginning with a verb, that provides actionable student items. These outcomes should be used to identify what can be assessed at the conclusion of the lesson and then be used to guide the planning of the lesson events. From the standards and student outcomes a teacher can create the enduring understanding of the lesson, which focuses on the larger concept of the experience that can be applicable to situations beyond the lesson. The driving question is created to provide students with an open-ended question that promotes inquiry about the concepts involved in the local or global issue. Subsequently, the teacher can highlight specific STEM-related careers that are relevant to the situation and ensure that students achieve an understanding of what professionals in these careers do. Lastly, the teachers can utilize an updated version of the 5E model for planning learning activities developed by Bybee (1997) and modified by Burke (2014). This model breaks the lesson into five different nonlinear phases that promote student-centered learning necessary to design, make, and evaluate a possible solution to the complex issue at the center of the lesson. Figure 2 illustrates this integrative lesson planning process.

As Burke (2014) explains, a modified version of the 5E model that includes engineering can be used to develop a student-centered learning environment that blends the benefit of both design- and inquiry-based learning. In Figure 3,this model is explained in a lesson plan format (Strimel, 2014b).

Teaching the Engineering Design Process

The engineering design process is more than just applied science; it involves an iterative process of transforming problems to solutions (NGSS Lead States, 2013). The engineering design process is a problem solving method used by engineers that applies knowledge from multiple domains including mathematics and science to solve technological problems (NAE & NRC, 2014) through a nonlinear process described as defining a problem; identifying constraints; establishing criteria; generating possible solutions through research; and developing, modeling or prototyping, evaluating, and optimizing a design. The authors have included the problem solving activity in Figure 4 to introduce students to the engineering design process. This activity is only designed to engage students and provide a context for learning about the engineering design process. This activity is not meant to engage students in an authentic problem solving experience. In the activity, students are first given the problem to solve and then, through instructor questioning, are guided in the development of their own version of a simplified engineering design process based on the steps they used to solve the given problem. The student-generated steps must then be elaborated on to include optimization, modeling, and analysis. Once again, this activity is only to be used to introduce students to the engineering design process; it does not intentionally teach specific engineering concepts or skills because it does not involve an authentic problem pr the use of industry-quality tools and materials.

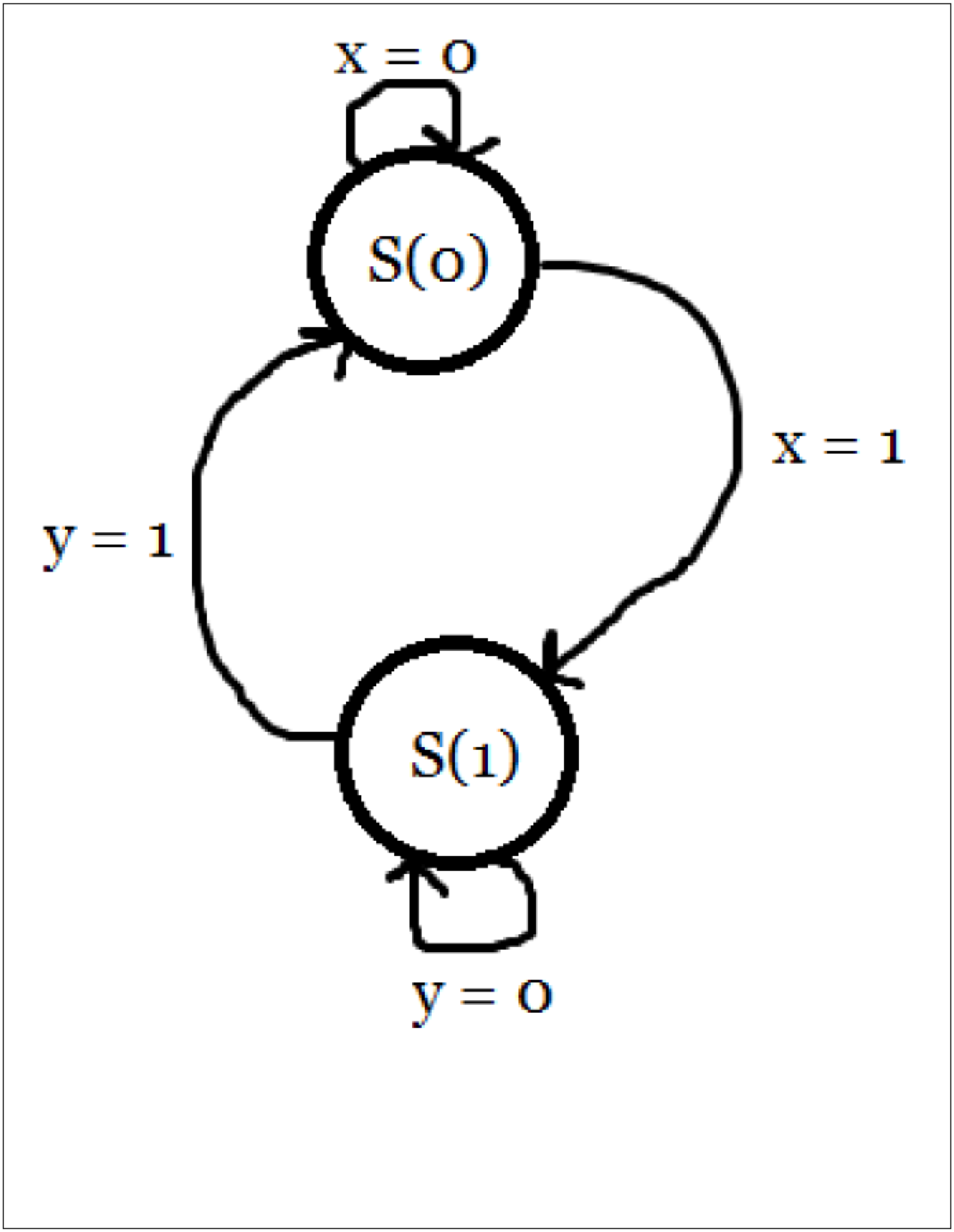

Figure 4. Engagement activity to introduce engineering design.

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Conclusion

The absence of engineering education in many K–12 classrooms represents both opportunity and uncertainty. Foremost, it provides a context for educators, specifically science educators, to strengthen their relationship with technology and engineering teachers to lead their schools in providing students with valuable learning experiences and fuel student interests in STEM. "Every young student deserves the opportunity to experience such awe-inspiring moments as watching a rocket race toward the sky and feel empowered to develop solutions to our world's most daunting problems" (Milano, 2013, p. 16). Engineering design, which encompasses aspects of problem- and project-based learning (Gómez Puente, van Eijck, & Jochems, 2011), is an essential component for integrating science with engineering, technology, and mathematics as well as other school subjects. As a distinctive form of problem-based learning, engineering design provides a basis for creating connections to concepts and practices from mathematics or science and enabling an I-STEM ED learning environment (Sanders, 2009). Moreover, authentic engineering design experiences and ill-structured challenges are a necessary tool for science education programs to provide students with the STEM knowledge and abilities that are considered necessary for fostering innovation and economic success. However, one cannot assume that a problem-based approach automatically means STEM disciplinary integration. Therefore, in Figure 5, the authors provide the recommendations for using engineering design to provide students with an integrative and authentic learning experience. Because little is known about student cognition during such experiences, future research can provide additional implications and instructional resources to guide implementation.

1	Utilize engineering design problems as a way to make ongoing, intentional, and natural connections to other subjects.
2	Employ engineering design problems that vary in structure to ensure that students are required to apply prior knowledge and to generate new knowledge.
3	Collaborate with technology and engineering teachers to go beyond having students solve problems using unrealistic technological tools and materials.
4	Require students to truly engage in engineering design by optimizing solutions through modeling and analysis.
5	Utilize authentic engineering design problems as the context for relevant transdisciplinary learning.
6	Design lessons using the student-centered format provided in this article.

Figure 5. Six recommendations for successful engineering design.

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Gateway Experiences to Engineering Technology: Development of an Introductory Course

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Abstract

The launch of a new Engineering Technology undergraduate degree at a research intensive university prompted collaboration from six different disciplines within the College of Technology. With a flexible curriculum designed to meet existing and future workforce needs, the program of study incorporated both new and revised courses. One of the new courses is a gateway Introduction to Engineering Technology course designed to attract and retain both traditional and nontraditional students. In this introductory course, engineering technology is defined based on the skill set needed for the current and future economy. The gateway course employs a reverse course-content-delivery design whereby students engage traditional lecture-based subject matter in a user-friendly manner that encourages students to revisit lectures on-demand. Students work through a series of at-home assignments in a linear manner, labeled simply as *read*, *watch*, and *do*. These assignments build upon each other to develop both depth and breadth through repeated exposure and analysis of core concepts. This is consistent with learning theory literature, which is replete with studies showing that when students experience expectation failure, followed by a time of thorough and investigative feedback loops, learning gains are increased almost fourfold, from 20–30% to nearly 80% (Karpicke & Roediger, 2008). In addition, based upon student persistence theory (Tinto, 2003), common student experiences are developed for both engineering technology content and the social learning aspect of higher education to create learning-communities for the gateway students (Tinto, 1997).

Keywords: STEM education, course organization, mixed instructional delivery methods, learning communities, learning gains, engineering technology

Advanced technical education must respond to the ever-changing needs of the workforce. Because it is difficult to understand, predict, and forecast workforce needs, educators mitigate this lack of understanding by thinking dichotomously about the short-term and long-term results of student learning. Short-term goals and objectives revolve around the knowledge and skills of particular cognate areas that are generally organized as academic units divided into distinct departments on college campuses. Long-term goals cross the boundaries of subject matter experts and are increasingly interdisciplinary. Employers are increasingly calling for technical, higher education to produce graduates that are prepared for a global economy based upon a foundation of technical expertise. Beyond a particular technical core, economics today demands individuals who are technical, flexible, self-starting, engaged in change, and mindful. *Mindfulness* can be defined as continuous discovery, constantly looking for adaptive and innovative ways of doing things and not relying on the status quo (Langer, 1997).

Engineering technology educators acknowledge that there is a "half-life" of the specific subject areas of technology and engineering. Due to globalization and other factors, technology-specific knowledge is rendered obsolete at a more rapid pace than with other academic disciplines (Smerdon, 1996). This speed of change should give pause to instructors as they evaluate what to include in their courses. The decreasing residual application of knowledge gained during a typical 4-year degree program has significant implications for the long-term impact of technology education and the problem-solving and critical-thinking foundations that students need from graduation onward. Educators must evaluate prospective technical models prior to integration into course curriculum in order to determine if the technology change will result in improvement to a student's academic experience and overall learning gains.

This paper promotes a model for advanced technology education that employs interdisciplinary thinking and preemptive program-development techniques through a gateway concept. The anticipation of changing knowledge domains and competencies that engineering technology graduates will need over the next decade were seamlessly integrated to address these authentic problems within the curriculum (Senge, 1990).

Recently, Schwab (2010) noted the national emphasis for advanced technology education as a strategy for the preparation of our graduates to compete globally. The National Academies' report, *Rising Above the Gathering Storm* (National Academy of Sciences, National Academy of Engineering, & Institute of Medicine, 2007), declared that federal needs revolve around preparing our workforce for requirements across the spectrum of the economy, specifically in the engineering and technology fields. Innovation is an increasingly important characteristic of the new economy that involves both the theoretical and applied disciplines (Stokes, 1997). This proposition has meant educating not only more engineers but also more engineering technologists. The National Academies' report on the state of education performance at all levels illustrates why an evolving and flexible academic curriculum is in order (National Academy of Sciences, National Academy of Engineering, & Institute of Medicine, 2007).

Indiana, like many other states, falls short of the workforce's educational attainment levels requisite to compete in a global environment (U.S. Census Bureau, 2011, Section 4, Table 229, p. 151). A key to continued competitiveness is having an educated workforce that is trained for the 21st century with foundational skills and competencies that will enable workers to succeed in fields not yet imagined. Currently, Indiana ranks 41st among all states (tied with Tennessee) for the overall percentage of its adult population holding a bachelor's degree (U.S. Census Bureau, 2011, Section 4, Table 229, p. 151). Furthermore, the state's demographics show an increasingly aging population, which further threatens Indiana's position as a tech-savvy business-friendly environment and may widen the gap between the skills the workforce possesses and what will be required, much less desired, in the next 5–10 years (Gamble, 2010). The potential problem is best exhibited by the major industries represented in the state. Indiana has a considerable manufacturing representation, constituting 19% of the total private sector employment. (Indiana

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Business Research Center, 2013). The business climate report indicates that the Indiana workforce lacks a global mindset, believes itself to be entitled, and lacks sophistication (Northeast Indiana Fund, 2009). Manufacturing alone represents a need for a broad spectrum of essential skill sets and workforce competencies, large portions of which are addressed by the program components in an Engineering Technology (ET) degree.

To meet these needs, the ET degree program delineated in this paper was developed at a research-intensive institution in the Midwest. Engineering technology has been recognized as a field primarily focused on engineering and technology ideas and values and the broad-based technical skills required for the development of cutting-edge solutions through the application of these competencies (U.S. Department of Labor, U.S. Bureau of Labor Statistics, 2010). This is different than traditional engineering programs that focus largely on theoretical concepts in the engineering disciplines.

Engineering technology is an area that "'emphasize[s] the teaching of industry-standard technological information and skills'" as well as competencies and knowledge domains, "'prepare[s] graduates to be immediately productive in society,'" increases graduates' value to society, integrates general and technical skills and knowledge, and is "'responsive to changing market demands'" (Gentry, 1995, p. 52; as cited in National Science Foundation, 1996, p. 60). Although these principles are well defined and constant, the specific applications, exhibited through the demand for engineering technologists, continue to evolve at increasing rates, and thus this paper serves as a guide to educators in evaluating and revising engineering technology programs as society demands continue to change.

Development

Engineering technology could represent educational-development purposes for growing K–12 programs. Expanding the program to include a K–16 mindset could help educators understand a pathway approach to engineering technology. This pathway would help higher those in education to understand that the economy requires individuals educated across a broad spectrum of job opportunities. Barbieri, Attarzadeh, Pascali, Shireen, and Fitzgibbon (2010) describe an educational model whereby students self-select based upon personal preferences, in this case, either engineering or technology fields. From a national perspective, personnel trained not only in the areas of science and mathematics but with the full integration of engineering and technology disciplines represent the full STEM model. Literature, legislation, and other STEM initiatives fall short of fulfilling the full mission of STEM. Such programs are commonly subsumed under the *E* of STEM. Yet, literature and history suggests a specific need for and thus a call to action to develop programs specific towards the *T*.

The need for STEM education encompasses efforts from primary through higher education levels (Kelley, 2010). Interconnecting STEM areas requires blurring the current academic boundaries to fulfill these needs (Kelley, 2010; National Science Board, 2007). To guide the development of an engineering technology degree, principles of integration should be defined with the same diligence. In higher education, this integration is defined as an interdisciplinary process. "*Interdisciplinary* understanding has been defined 'as the capacity to integrate knowledge and modes of thinking drawn from two or more disciplines to produce a cognitive advancement . . .' (Mansilla, 2005, p.16)" (Kelley, 2010, p. 2). According to Kelley (2010), the advantage of interdisciplinary learning is to create understanding that is unlikely through a single discipline. The blurring of disciplinary boundaries advocates for development of integrated STEM curriculum and is a premise that guides educators in developing an engineering technology degree (Bredderman, Burghardt, Hacker, & Peruzzi, n.d.; Kelley, 2010).

Engineering Technology Plan of Study

The field of engineering technology has been well documented as an academic discipline (O'Hair, 1995). This ET degree was created based upon inquiry and discussion with multiple stakeholders including industry, alumni, and legislative representatives.

The ET degree program is based on a foundation of STEM fields and draws from cognate areas represented by many academic departments, including a broad range of program experiences. The Electrical and Computing Engineering Technology program offers an applications and lab based curriculum that combines practice with electrical theory. Technical and professional skills allow students in this program to analyze, design, and implement systems for control, communication, computers, or power. The Computer Graphics Technology program prepares students for careers in creating and managing the production of computer graphics within a wide range of industries. The Computer and Information Technology program prepares students for careers in information technology systems or networking. Students go into a number of diverse fields such as healthcare, manufacturing, and law enforcement. Students in the Industrial Technology program are prepared from a technical basis for the management, operation, and maintenance of complex technological systems across a wide range of fields. Graduates of the Mechanical Engineering Technology program are prepared to plan manufacturing systems based in automation and incorporating people, processes, and technology. Finally, the Organizational Leadership and Supervision program offers a practical approach to leadership recognizing interpersonal and change implementation practices.

The importance of good communication skills is consistently publicized as a workforce requirement for college graduates, especially for those in highly technical areas of study (Bruzzese, 2011). Therefore, to extend degree usefulness beyond technical proficiency, students should be able to document and present technical information in written and oral form to technical and nontechnical personnel (Bruzzese, 2011). As a program objective, ET graduates have the ability to recognize that industry needs incorporate important skill sets such as project management, collaboration, and recent operations innovations (such as lean manufacturing) combined with traditional engineering principles (Hotler, 2002). In order to complete the program objectives, the curriculum is broken down in the following areas:

- General Education Courses (46 credit hours),
- Required Technical Core Courses (51 credit hours)
- Technology Selective Courses (18 credit hours), and
- Electives (9 credit hours).

The ET plan of study and overall program objectives serve both students and industry clients by developing and employing technical knowledge, problem-solving techniques, and applied engineering and technology skills in traditional and emerging areas. ET graduates will be prepared to actively participate in ongoing professional development for professional career growth. The foundation of these characteristics enables an advancing career path that is evidenced through gradually increasing professional responsibility or job scope.

Technology faculty must respond to the requirements of student assessment and ensure that

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graduates of engineering technology programs meet both the expectations and standards of the institution and other stakeholders, such as private industry (EHR Advisory Committee, 1996), through accreditation by a nationally recognized body, such as the Technology Accreditation Commission (TAC) of the Accreditation Board for Engineering and Technology (ABET; Barbieri, Attarzadeh, Pascali, Shireen, & Fitzgibbon, 2010). ABET's outcome-oriented standards emphasize learner-centered instruction and measured learning

The use of general electives allows faculty and students to craft the specific academic concentrations within the ET program. The ET degree program is designed to remain rooted a technical discipline, but it is also designed to be flexible and adapt to unknown future career options and respond to the exponential growth of technical options in the general economy.

The challenge of flexibility includes introducing students to the discipline. Although each of the concentrations in the ET program share the same foundation, students need a planned and deliberate introduction to the engineering technology discipline in order to choose particular program offerings based upon what they want to do.

Students may meet unique regional needs through selecting concentrations within the overall ET program of study. The ET degree has concentrations that were developed based upon the workforce needs of particular growth regions based on regional economic clusters known as Indiana Economic Growth Regions (Indiana Department of Workforce Development, 2005). The Economic Growth Regions serviced by the Bachelor of Science in Engineering Technology encompass 33% of the state workforce (Workforce Development Associates, 2007).

Course Design

Ensuring flexibility in the degree program is a significant challenge because the program must also ensure that there is consistency across student experiences. This challenge also surfaces in the literature related to the academic success of engineering and engineering technology students. Studies have shown that institutions should integrate learning communities throughout their programs to further increase learning gains, student retention, and graduation rates in the STEM fields (Tinto, 2002).

The integration of these diverse ET degree components requires extensive faculty collaboration to provide a common student experience that is rigorous and ensures the necessary cohesion between the sets of courses and their respective, diverse, expected outcomes. Employing the concept of a "gateway" experience is key to introducing students to an interdisciplinary degree program and provides a means for faculty to collaborate across their particular units. An Introduction to Engineering Technology course has been created to provide this gateway experience. This course serves to establish a baseline set of student competencies that will be built upon in later courses.

The gateway course introduces students to the different disciplines that comprise engineering technology in a polytechnic manner and includes systems engineering, quality improvement, and management of processes and projects. The overall skill sets needed by a technology worker are introduced, including problem solving, communication, teamwork, and professional development. A goal of the course is to provide focus, including a holistic approach to technology systems. This class provides a transition point for students by introducing learners to a pseudocohort classroom experience at the beginning of the ET curriculum, which includes integrated use of active learning techniques, such as peer learning. In addition to introducing the diverse disciplines to students in a seamlessly threaded package, the gateway course provides a common experience that promotes more student involvement in the classroom via collaborative learning through *shared knowledge* and *shared knowing* (Tinto, 1998; see also Zhao & Kuh, 2004). Students construct and discover shared knowledge for an enhanced cooperative learning experience, which includes linked activities tied to the curriculum for a common coherent experience (Tinto, 2003). Shared knowing is based upon students sharing a particular transition point, such as becoming freshman, or an initial educational experience (Tinto, 2002).

Students in the gateway course actively participate through a social-learning model to explore issues and ideas. Instructors guide students as they progress through the development of learning communities in which students present and disseminate their individual and group research outcomes on the various topics assigned throughout the course (Brower & Dettinger, 1998). A focus on student learning underpins their peer-based active learning experiences and sets in place a foundational tenet that will be employed throughout the remainder of their academic careers (Cross, 1998). The method of designing content by integrated modules rather than discipline-specific content areas was done to aid the students in interpreting and evaluating engineering technology as an integrated whole. By designing the course to minimize the perceived differences between the various academic units, the expectation is that students will create connections between content and industry regardless of which department a specific content module came from.

For application activities, problems of a technical, operational, and human nature are introduced and investigated as part of in-class work. Graduates of the program will satisfy employers' desire to hire candidates who are continuously striving to expand their knowledge base about internal positions and processes outside of their immediate area (Di Meglio, 2009). With a very specific and rigorous content and modular-design philosophy intact, the program includes multiple delivery approaches to allow for different ET locations to coordinate classes in a traditional, distance, synchronous, asynchronous, or hybrid manner.

Modular Approach

For this gateway course, the content was created as modules intended to meet the course objectives, and to tie the diverse course content together. One module was created to address each objective presented in Table 1.

This course was delivered across the state at four geographically disparate locations that complicated the design and deployment. Therefore, a great deal of strategy was needed when creating the criteria for each module because content needed to be reusable, timeless, and effective. The modules provided the core content in the form of a self-contained, platform-agnostic audiovisual presentation. While there are an increasing number of academic and nonacademic institutions and individuals who are contributing to the bourgeoning amount of online course offerings, tutorials or minicourses, and refresher-lessons, the intent of those types of programs is significantly different than the intent of this program. The faculty were charged with developing course materials that could supplement classroom instruction to further cement the knowledge domains in a student's mind. The course designers wanted to ensure that instructors or students would not have to mentally remove irrelevant references while viewing online lessons.

Specific design criteria for modules were shared with subject matter experts who agreed to contribute to the overall course design, which included "timelessness" or plug-and-play design characteristics. The modules were to be recorded without reference to time, department, or any other external information that identified a particular module beyond the core content of the

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information delivered therein. In this way, no external references were given that might have otherwise conflicted with the use of a given module during a particular semester.

Table 1
Introduction to Engineering Technology Course Objectives

Students will be introduced to various aspects of computer modeling, including solid/surface modeling.
Students will be introduced to various aspects of computer simulations, including animation, and multimedia/web applications.
Students will be introduced to multitier applications including user and machine interface, application software, and database components.
Students will be introduced to the infrastructure of computer networks.
To provide students with an introduction to the technology and provide them with a working knowledge of basic electrical quantities (voltage, current, resistance, and power)
Understand the difference between AC and DC, their units (volt, amp, Ohm, Watt), their "role" in electrical technology, and safety as it pertains to working with electrical systems
Student will understand disciplined problem-solving tools and apply them for continuous improvement.
Demonstrate understanding and application of basic organizational and management concepts
Apply the general solution format known as GFSA, Given-Find-Solution-Answer.
Apply both U.S. Customary and S.I. (metric) units, and the factor-label method of converting units.
The student will learn how to form and work in teams and work in collaboration.
The student will understand how to lead multifaceted groups.
Students will understand and apply university library resources.

Therefore, having modular-consistency was crucial to the overall success of the modular approach. The subject matter experts and course collaborators were given the following criteria for the modules. Each module should be:

- Clear in its definition and use of acronyms or common terms from the field in question.
- Concise in its discussion of specific subject matter and avoid presenting tangents that may have otherwise related to the subject matter in a normal program curriculum but does not in this case.
- As short as possible to cover the required content, given that students would normally be watching these as a part of their homework assignment and attention spans are not very long (suggested length was between 25–45 minutes).
- Fully self-contained and not require links to external websites that may not exist in the near future.
- Executable on any operating system platform (i.e., the modules were to be platform agnostic).
- Auto-executable and not require students to purchase or install extraneous software.
- Devoid of any references to a temporal event that would potentially render the module outdated.
- Devoid of any references to any specific instructor, professor, or other persons

associated with the program, college, or university.

- Devoid of any references to any specific department, name, course numbers, acronyms, or other programmatic terms.
- Devoid of any references or instructions directing students to complete any portion of an assignment, task, etc. as part of the ongoing class.
- Devoid of any references to any other aspect of the actual course, course delivery timeline or method, in-class case studies or activities, course management system (e.g., Blackboard), or any other aspect of the course that may change in future iterations of this course.
- Produced on a technology platform that is consistent with the other modules, given that specific subject matter or content may require a specific technology.
- Produced on a technology platform that allows for minor changes or edits post-facto.
- Searchable via a digital Table of Contents (TOC) and allow for adjustable playback speeds should a student wish to replay or skip only specific portions of the video lesson.

Working to develop content that is generic yet can be reused easily was a challenge in some areas, such as the library module in the gateway course. Ideally, library content is directly tied to a task, or set of tasks, that students are currently working on in a class, thus leveraging the ability to apply the new knowledge in a specific context and assist the retention of new information or processes. For a collaborator who was not involved in all of the course development discussions, it was a challenge to develop the module so it will have the most benefit to the students and the work being done for the overall course project. This exemplifies why it is critical for the core modules to be discussed during class because without a pragmatic discussion and distillation of concepts introduced in a video lecture, students would be very unlikely to retain any knowledge in a permanent and applicable manner.

Throughout the semester students progressed through an iterative cycle in which the students would first be assigned homework, where the students would first read any assigned reading to introduce a content area; then watch the module assigned for that same content, which would help to further elaborate on material; and then complete a hands-on assignment. We called this the “read-watch-do” cycle of learning. The second part of the overall approach involved the in-class work following the read-watch-do cycle. Subject matter experts who agreed to provide content in accordance with the prescribed criteria were also asked to provide course materials to be used in conjunction with their respective video lectures. This content included suggested in-class, hands-on activities or additional lecture notes or discussion points that helped students digest and distill the concepts delineated in the video. During the in-class session, students take a prequiz, both to ensure homework completion and to inform the instructor about areas of confusion for the students. The students would then participate in an in-depth class discussion and distillation of the homework material. The discussions were directly tied to the module material and provided otherwise missing components to aid in the dissection and digestion of the modular content and providing application and relevancy of the content. The at-home modules allowed for faculty to spend class time creating the relevance necessary to increase learning gains rather than spending the lecture time merely introducing the material. Students

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assign a higher task value to assignments they see as relevant. Relevance is enhanced when the applicability of the content is explained and applied to real situations and tasks that students will be asked to complete as a professionals.

The class discussion was followed by another hands-on activity that was designed to be an advanced use of the original homework done before class. For example, a student may have been assigned homework to collect some data (e.g., observational data about resistor tolerances) and conduct a preliminary assessment and analysis of that data. After the class discussion, the instructor would then walk the students through a second, more in-depth analysis of the same data, which provided further relevance.

There was much discussion among the course design faculty on how to integrate the differing material into one cohesive and integrated course. The conclusion was to create a semester long project that integrated the course material and involved field trips, case studies, and practical, applied content. The problem or case study activity selected was related to wind power generation and distribution. The case is not presented in the modules in order to preserve their reusable or "timeless" characteristic and is instead directly incorporated into the classroom sessions. Designed in this manner, the case study can be changed as time and technology progression allows, leaving the core lecture content in the modules unchanged, and the faculty are responsible for taking the content from pure theory to real-world applications. The case study helped thread the different material together by integrating modules through student engagement.

Learning Communities

The faculty's goal was to have a case study in which students produce artifacts that demonstrate competency with the material and that is collaboratively built as a cohort. Therefore, one course feature is the inclusion of social learning. Social interaction, particularly dialogue, has received little attention in the engineering technology related pedagogical literature but warrants conversation. A fundamental feature of the gateway course has been the utilization of a learning community aspect to foster knowledge in a dynamic social setting. Many of the students obtaining a degree commute to and from, as opposed to residing on, campus. As a result, interaction outside of the classroom is limited. With the inception of the ET program, the intent was to create a holistic learning experience that compensated for student living arrangements and enabled relationship creation at the foundational level of the program by fostering social interaction and nurturing academic growth through collaborative activities.

Although academic success may be achieved on an individual basis, often the by-products of group alliances yield more insightful and intellectually grounded outputs for students, ultimately resulting in increased learning gains (Terenzini, Cabrera, Colbeck, Parente, & Bjorklund, 2001). In this course, students were assigned the task of collectively producing a research wiki, which was to contain research produced by students not only from their own course site but from all other sites offering this course. Each campus conducted a literature review, and each student posted his or her citations, analysis, and discussion of the literature to the wiki. These wiki-based literature reviews were then accessible to all students enrolled in TECH 105 throughout the state. In this way, students were exposed to a real-life situation in which they were required to produce a significant final product through the collaborative efforts of geographically dispersed individual contributors. By the end of the semester, the wiki created by the students included all relevant research articles, a synopsis of those articles, and final presentations and papers of the interdisciplinary issues related to wind energy and engineering technology.

Most importantly, the online dialogue was the first step in students beginning to view one another as colleagues or even friends. It is common knowledge that interaction between friends varies greatly from interaction between acquaintances. The course design took into account the premise that if friendships are established early on, the students would be socially fulfilled and student persistence and probable advancements in engineering, science, technology, and math would occur at significant points in the student's college career. It is believed that learning communities assist in the accomplishment of that goal. Stimulating learning in a community setting ultimately results in student persistence and learning.

In the learning community modules, students were given the opportunity to explore the effects of cooperation and competition among group members to solve a group problem presented in the form of a puzzle. Members were intentionally chosen to demonstrate cooperative or conflicting behavior. The objective was to raise student awareness regarding how cooperative behavior is more conducive to achieving results in a group setting. In addition to activities that foster social interaction, intellectual activities were also chosen. Students in a social learning context put more effort into social educational activities that enable them to bridge the academic–social divide, make friends, and learn at the same time (Tinto, 2003).

A second learning community activity was an all-classes field trip. Early in the semester, students from all sections (all statewide locations) attended an on-site industrial tour of a manufacturing plant. As a subgoal of the trip, students were matched with a peer from another location and provided with an opportunity to socialize while cooperatively completing a "Site Inspection Checklist" during a plant tour. The trip brought many of the research intensive university ET community together, even if only for a short time. The tour gave students the opportunity to interact with peers, business personnel supporting the degree program, and see principles of engineering technology applied to industry. These transactions were then reinforced and continued through the use of the class wiki.

The final learning community activity focused on being able to identify the factors of effective communication during problem solving, especially those related to graphical visualization of engineering data. Striving to understand the message with clarity and without interruptions can mitigate the chance for miscommunication. When communicating in a group setting, the possibility exists that not all group members receive and interpret messages the same way, resulting in ineffective communication. Students learned that active listening and reflection during the decoding phase of communication are key components to this skill set and, when done with intention, leads to a clear sense of understanding. There is statistical evidence that students who are involved with the people and activities of learning communities are significantly more likely than their less involved peers to show growth in intellectual interest and subsequently are more likely to get more out of their college education (Tinto, 2003). The progress, retention, and success of this cohort will be monitored as they progress through the ET program to measure if the camaraderie fostered through the gateway course made a substantial impact.

Results and Conclusions

The Gateway course is delivered across multiple ET locations. The flexibility of the ET degree meets the statewide needs of the Indiana workforce and community and is being viewed by the stakeholders as a model that can be deployed on a national scale by other mission-related

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organizations. Engineering technology as a discipline will provide graduates with a solid foundation in engineering principles, allowing for flexibility and specialization to meet particular industry and regional needs. Finally, the flexibility of the ET degree lends itself to diverse and remote delivery methods.

The ET degree is delivered across multiple locations to reach students that are embedded in their community. With a statewide mission, there is an opportunity to reach students who might not go through a more traditional path. The challenge of effectively allocating limited resources while providing a consistent level of rigor through a variety of delivery methods is also ever-present. The flexibility of the ET degree also allows for variability in the administration of the program while recognizing the challenge of employing local resources to deliver the content of the ET program, hence, the need to create flexible, reusable, and malleable program curriculum that can be tweaked to fit a specific regional-industry need.

A future outcome of this work that might be of interest to the academic community would be to understand how to create reproducible processes for interdisciplinary course design for ET programs. Coordination among faculty is a challenge requiring conversations leading to trust, for the purpose of science. "Werner Heisenberg (formulator of the famous 'Uncertainty Principle' in modern physics) argues that [the field of] 'Science is rooted in conversations . [. . . and] The cooperation of different people may culminate in scientific results of paramount the utmost importance'" (Senge, 1990, p. 238). With the roots of the ET program founded in science, technology, engineering, and mathematics, the cooperative learning model has been identified as the ideal framework, lending itself to academic achievement through group interaction. In order for the work to occur, dialogue among faculty is required to meet the needs of instructors to feel comfortable and at ease with the content. Prior to the course design phase, free flowing conversations and dialogue, peer introductions, familiarization, and acceptance must occur. During the course design, social and intellectual interaction for the purpose of learning was identified as a fundamental component of the program. It turns out that interaction is a primary artifact of the design process among faculty as well. If the only thing that is sustainable in an organization is the interaction among faculty, this may hold true as a result of this process as well.

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