AC 2010-2280: LEARNING THROUGH ENGINEERING DESIGN AND PRACTICE: IMPLEMENTATION AND IMPACT OF A MIDDLE SCHOOL ENGINEERING-EDUCATION PROGRAM

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Learning through Engineering Design and Practice: Implementation and Impact of a Middle School Engineering-Education Program

Abstract

This paper describes research efforts and results of the first year of a two-year long technologically centered discovery-based extracurricular learning experience designed and delivered to over 100 seventh-grade students from four middle schools. Research methods used to study program impact included statistical analysis of pre- and post- tests, qualitative research techniques of eliciting information using subject-produced drawings, journal writing, focus groups, and observation. This project is sponsored by the National Science Foundation (NSF) funded Information Technology Experiences for Students and Teachers (ITEST) program aimed at enhancing traditionally underrepresented youths' interest in Science, Technology, Engineering, and Mathematics (STEM) subjects. Disciplinary experts were drawn from materials science, industrial engineering, mechanical engineering, computer science, sustainability, science education, mathematics education, cognitive psychology, counseling, and education research methods. These experts worked with K-12 educators to design and deliver an extra-curricular middle school engineering education program.

The program utilized the engineering design process as the fundamental construct for engagement with the novel teaching and learning experiences. The program provided experiences where participants learned engineering and information technology skills through activities such as simulating desert tortoise behaviors, and researching and developing designs to mitigate the urban heat island. They also participated in leadership development activities over the summer serving as docents for younger children at the local science center, a research internship with the university, and an industry internship with a local energy and water service provider.

Student learning was assessed using formal and informal methods. Informal assessments consisted of whiteboard presentations, open-ended questioning, demonstrations, journal write-ups, and teacher observations. These were used to guide daily activities and lessons. Formal assessments consisted of pre and post assessments. Subject produced drawings were used to elicit students' pre- and post-program knowledge. *Draw a Robot* and *Draw an Engineer* assessments were used. A survey instrument was developed and implemented to elicit tinkering and technical self-efficacy. An earlier developed instrument that was validated using a sample of responses of 200 engineers to develop the items was modified for use with youth. Observations of project activities by external evaluators, interviews with educators, school administrators, program facilitators, principal investigators, industry volunteers, collaborators, and student participants, were used to study whether project and research goals were met.

Pre and post assessments in the form of open-ended questions related to content in major units were administered. Assessments were analyzed to determine what impact the project had on student learning and student interests in related STEM content. A two-way repeated measures ANOVA was conducted on each unit to compare differences in the relationship between pre and

post assessment scores. Data revealed that by engaging youth in learning experiences that emphasizes both utilitarian and inquiry-based motivations, where learning is made relevant to students' lives, the outcome leads to enhanced learning in content areas. We have also learned that systematic efforts are needed to dispel misunderstandings regarding STEM subjects and professions. Coordinated and carefully designed in-depth and long-term experiences are needed to provide students and families with knowledge of STEM education and career pathways.

Perspectives and Theoretical Framework

Research has shown that the public does not believe that engineers are engaged with societal and community concerns[1]. Whereas, in reality, engineering has existed as long as humans have had needs. Engineering has to be viewed as an ethical human endeavor that addresses the needs of a global society. Engineers are inventors and designers; they apply science and mathematics; and use their imagination and creativity to make ideas a reality. They create technical solutions to meet societal needs. This forms the core of engineering activities[2,3]. Yet, there is a decline in high school students' interest in careers in science and engineering resulting in a decline in engineering enrollment, both undergraduate and graduate. Engineering doctorates have declined in recent years and are still below the levels of the 1980s[3].

Adolescents seldom lack curiosity, but as they go into the teenage years their enthusiasm for learning Science, Technology, Engineering, and Mathematics (STEM) subjects appears to decline[1]. Many drop out before the end of required schooling. Others continue to turn up for school but make the minimum effort. These problems take on new meaning in a period when a fundamental survival tool for individuals, and nations, is the willingness to learn and re-learn, i.e., engage in life-long learning[4]. Trade liberalization, globalization, fast-changing nature of work, and ageing populations have impacted the distribution of employment opportunities.

Low-skill jobs are disappearing; people are switching jobs more often; and demands for highly skilled professionals in developed nations such as ours are growing rapidly. Also, significant differences in educational attainment remain with regard to ethnicity, origin, age, and sex. These educational gaps are reflected in the National Assessment of Educational Progress (NAEP). The performance gap for Hispanics, American Indians, and African Americans in comparison to Whites and Asians exists in all subjects; it is more prominent in Science. In Arizona, 77% of American Indians, 72% of Hispanics and 68% of African Americans performed Below the Basic level in comparison to 32% Whites in the 2005 NAEP eighth grade Science assessment. Further, engineering is among the least gender equitable professions with a workforce that is only 11% female and STEM programs continue to have low minority enrollment[5]. The cause has psycho-sociocultural roots that create barriers to female and minority participation[6].

Evidence suggests that when students' families, schools, community-based organizations, science and technology centers, and institutions of higher education, come together to provide carefully designed learning supports for traditionally underserved students, these learners are noted to have performed at high achievement levels[7]. A multi-disciplinary team of content experts and public and private collaborators must approach the curriculum implied in this challenge. Such a program must also include the potential to engage parents, educators, and relevant community members in authenticating students' experiences. Informal learning settings outside the framework of schooling offer the potential to stimulate interest, initiative, experimentation, discovery, play, imagination, and innovation in learners[8,9]. Engaging learners in activities where they test ideas and concepts, apply them to a new situation, and integrate the new knowledge with pre-existing ideas may very well be an approach that can enthuse students to attain the goal of becoming future scientists, technologists, engineers, and mathematicians. Sullivan[10] advocated an integrated K-16 approach towards engineering education that establishes long-term knowledge and skill building relationships between K-12 and higher-education settings.

It is important to note that the workplaces of today and tomorrow demand skills that are not merely exemplified as technological—logical, analytical, and technical, but also those represented as value skills—creativity, critical thinking, ability to see the big picture, and work with diverse individuals[11,3]. These are workplace skills mentioned in the U.S. Department of Labor[12] Secretary's Commission on Achieving Necessary Skills (SCANS) report that are essential in the development of our youth as future scientists, technologists, engineers, and mathematicians. Educational experiences within the K-12 school settings, colleges, and universities need to engage youth in not only the content knowledge, but also these technological and value skills. Further, the NSF[5] reported that current curricular approaches appear outdated and de-contextualized. Students need to be exposed to inquiry-oriented learning environments as a means of increasing their interest in the STEM fields. The case for fundamentally changing how we introduce students to these fields and careers is strong. This underscores the need to enhance early STEM interest, through in-school and out-of-school experiences, to influence the choice of high-school coursework and options for career and educational pathways. Engineering can serve as a means for the integration and application of mathematics and science in ways that connect youth to the joy of learning, and to applying knowledge and skills to socially relevant challenges[1,10].

Project Goals

The overall goal for the *Learning through Engineering Design and Practice* project was to present a technology centered, discovery-based, extracurricular learning experience for urban youth from underserved neighborhoods with a minimum of 120 contact hours per year for two years. Researchers envisioned student participants meeting the following short term program goals: a) gain in-depth knowledge of STEM concepts by working on intellectually engaging and socially responsible complex problems; b) learn collaboration, teamwork, and workplace skills mentioned in the SCANS report[12] through mentoring experiences that include interactions with adults, peers, and younger peers; c) confront stereotypes about females and minorities in STEM professions through cognitive apprenticeship offered by diverse mentors; and d) gain the necessary knowledge to engage with provided opportunities to explore STEM careers and educational pathways along with parents and guardians.

Project Design Principles

The project design followed the NSF Information Technology Experiences for Students and Teachers (ITEST) Program Solicitation 07-514 (2007) requirements to provide opportunities for 96 participants in grades 7-8, in two consecutive years of programming, with 120 hours of informal education (out of school time) each year. In this section we describe the underlying principles that inform the design of the *Learning through Engineering Design & Practice* project activities and the research and beliefs on which these activities are based. This endeavor incorporates a variety of strategies to engage middle-school youth and their teachers in in-depth exploration of STEM subjects using the engineering design process as the underlying framework.

The **Project-Based Approach** is an instructional strategy that helps students apply content knowledge to authentic problems, which requires critical thinking and increases students' responsibility for learning. This approach has its foundations in the curricular and psychological research work of Dewey[13], Kilpatrick[14,15], Stevenson[16], Piaget[17,18], and Vygotsky[19,20]. It was Dewey[13] who advocated that the most natural way for children to learn is by doing. He said for children to develop a habit of "critical examination and inquiry," they need to be provided with appropriate learning experiences and guidance (p, 29). Kilpatrick[15] defined *project* to refer to any unit of purposeful experience or activity, "where the dominating purpose, as an inner urge, (1) fixes the aim of the action, (2) guides its process, and (3) furnishes its drive, its inner motivation." Vygotsky[19,20] described learning as a social process that takes place in the context of culture, community, and prior experiences that is further enhanced when learners work collaboratively on challenging tasks.

Projects embedded in engineering design give learners the opportunity to explore: a) design, b) testing, and c) the production of tools, technology, structures, and materials. *Learning through Engineering Design and Practice* presented students with a series of projects over a year long informal experience. In our case, learners were presented with engineering design problems where solutions are achieved via an actual project. Participants had access to a wide range of resources that included human and content rich media, Arizona State University art museum and engineering laboratories, the Phoenix Zoo, the Arizona Science Center, a number of different types of hardware and software technologies. The *project* therefore is the culmination of the learning *process,* and the solution is the finished *product*[21,22,23,24]. Using a project-challenge that is analogous to complicated tasks encountered in today's STEM workplaces, student teams were confronted with a problem that acted as a focus for teamwork and a catalyst for multidisciplinary learning. The year long effort incorporated many problems that gave context to and serve as supports to learning[25,26]. Projects extended over time to allow students to acquire new knowledge and skills[27].

Our approach is learner centered and included multiple learning communities: K-12 teachers, informal educators, undergraduate and graduate students, members of professional societies, and STEM professionals. The project curricula were designed to develop in participants, the technical- and value- skills needed for STEM careers[28]. This approach is ideally suited for addressing engineering design projects, which are by definition open-ended with alternative solutions, where the problem acts as the catalyst that initiates the learning process[29].

Cognitive Apprenticeship has at its heart the idea of learning in context where the activity being taught is modeled in real-world situations. Brown, Collins, and Duguid[30] proposed that skills and concepts are best learned in their real-world context and situation. Cognitive apprenticeship is situated within the social constructivist paradigm, which advocates that humans generate knowledge and meaning from their experiences[19,28,31]. Lave[32] said that learning is a social process, and that skills are best acquired through authentic situations by communicating with peers and experts about those contexts. An example of a situated learning activity is more “apprentice like” and the learning activity is designed such that it is just beyond what a learner can attain on her or his own, but not at a level of difficulty where it is impossible to achieve with the help of peers and experts.

Learning through Engineering Design and Practice embedded cognitive apprenticeships in its year long endeavor. Representatives from the STEM industry and professional engineering societies, Arizona State University STEM faculty and undergraduate students, scientists, technologists, and content experts from the Arizona Science Center, the Phoenix Zoo, and others relevant to project content worked with the middle-school youth both in their workplaces and the informal learning space. Thus teachers, mentors, and experts worked side-by-side with the youth in addressing the project-based challenges. This approach was designed and incorporated into this effort to allow for implicit processes and knowledge of the STEM professions and career pathways to become explicit to participant youth via collaborative experiences.

The **Learning Cycle** is an inquiry approach to instruction and is a popular science instructional planning tool[33,34,35]. This approach has been researched for its impact on learning[36,37,38]. Its origins can be traced to Bruner[39] who introduced the notion of “discovery learning” where students interacted with their environment to discover new ideas. Initially described in the *Science Curriculum Improvement Study*[35], the Learning Cycle was based on three phases of instruction: exploration, concept introduction and concept application. Since its initial description, the Learning Cycle has undergone a number of variations. A more recent variation offered by Bybee[34] is known as the 5-E model—Engage, Explore, Explain, Elaborate, and Evaluate. The *Engage* phase is to capture learners’ interest and attention, and access student’s prior knowledge and conceptions while connecting it to the current learning experience. The *Explore* phase is to provide the learners with activities wherein the current concepts, processes, and skills are identified, and conceptual change is facilitated. The *Explain* phase is to provide the learners with opportunities to describe their understanding of knowledge, processes, or skill. The *Elaborate* phase is to provide learners with experiences to develop deeper and broader understanding, more information, and adequate skills through additional activities. The *Evaluate* phase is to provide learners with the opportunity to reflect, assess their understanding and skills while also providing facilitators with the opportunity to evaluate learners’ progress. It is important to note that these phases are by no means linear, rather they are cyclic. In *Learning through Engineering Design & Practice*, the Learning Cycle is used in the design of learning experiences with careful attention to each phase[40,41,42].

The idea of **Construction Kits** as tools for life-long learning where participants engage in engineering design and technology were embedded in the *Learning through Engineering Design & Practice* project-based challenges. All participants were expected to design, build, play, interact with various tools and each other, invent products, create art installations, and engage in socially responsible and intellectually stimulating real world challenges. Embedded in the learning experiences were the fundamental information technology skills of data analysis, modeling, the use of algorithms to test ideas, data display to communicate ideas, and synthesis of information.

Froebel[43], the father of kindergarten, described a series of objects and instructional materials that he called "Gifts and Occupations." The gifts were objects—a ball on a string, sphere, cube, rectangular block, and cylinder—which helped the child understand and internalize the concepts of shape, dimension, size, and their relationships. The occupations were materials—plastic clay, wood carving, paper folding and cutting, painting, interlacing, interweaving, stringing beads, etc—furnished to practice skills, leading to invention giving the child power. Forebel[43] stated,

> each gift should aid the child to make the external internal, the internal external, and to find the unity between the two. The occupations, on the other hand, furnish material for practice in certain phases of the skill…The gift leads to discovery; the occupation to invention. The gift gives insight; the occupation, power.

His principles of free self activity, creativity, social participation, and motor expression is the foundation for early childhood education. In our view, construction kits such as Erector sets and today's programmable Legos extend these basic principles to young people and adults of all ages.

Resnick and Silverman[44] strongly influenced by Papert[45,46] at the Massachusetts Institute of Technology (MIT)Media Lab have long advocated the notion of construction kits as systems that make possible for children and youth to design and create things both in the physical and virtual worlds. With these beliefs about learning through design, we incorporated the *ideas and tools* designed by the MIT Media Lab[47,48].

These research-based design principles formed the basis for the year long learning experience that was planned and delivered with attention to engaging all participants: students, parents or guardians, teachers, facilitators, and mentors. The specific project tools and multi-disciplinary content used to engage participants are described in the following section.

Project Tools

The use of robotics in K-12 education gives students the opportunity to design physical objects and mechanisms, to include designing the behavior of these objects using computer programming. Many researchers[48,49,50] have explored robotics to teach ideas in mathematics and engineering (e.g., control systems, computer programming).

Over the last few years, robotics-based educational programs have become a popular activity in the United States and around the world[51]. With the increasing popularity of programs like FIRST Lego League, students ages 9 to 17 are getting opportunities to build their own robots using programmable kits like Lego Mindstorms and VEX Robotics.

While one can argue there is nothing inherently wrong in introducing robotics in formal and informal K-12 learning settings by giving students the task of building a robotic vehicle and navigating mazes, we advocate that such efforts are narrow and limit student creativity. Such limited interactions do not engage the students to consider the broad scope and sequence of robotics. The area of robotics includes a large variety of programmable machines that carry out actions based on inputs from sensors. For example, a garage door sensor that detects when an object is in the path of the garage door, a home security system that sounds an alarm when it detects motion, a backyard rain gauge system that triggers the irrigation system based on its detection or absence of rain, and the microwave in the kitchen that can detect when the frozen entrée is cooked, are all instances of robotics that make our lives easy.

Our project goal was to attract female and other nontraditional populations to explore STEM subjects. Therefore, it was important to create learning experiences that were not embedded in technology for technology's sake (e.g., building bots for a robot race or a competition). Baker & Leary[52] found that girls liked learning science in a social context where they could interact with others and take part in learning experiences that did not isolate them. They also found that girls selected science careers because they had a strong desire to help. The American Association of University Women Educational Foundation-AAUW[53] noted that "Girls and other nontraditional users of computer science – who are not enamored of technology for technology's sake – may be far more interested in using the technology if they encounter it in the context of a discipline that interests them" (p. v). In keeping with our philosophy of promoting discovery and innovation, we wanted to offer diverse pathways into robotics as a means to engage with STEM education. This is essential if we are to ensure participation of individuals in the STEM fields who may have a diversity of interests. Therefore, giving students the choice to pursue experiences that interested them and had strong value connections was important.

We selected the following construction kits that had their origins in the research of the MIT Media Lab: a) The LEGO Mindstorms NXT robotics kit which is appropriate for developing mobile robots; and b) The PICO Cricket kit which is appropriate for the integration of art and technology. These construction kits come with a programmable brick, Lego bricks and wheels, a set of sensors (touch, resistance, light, ultrasonic, and sound), and mechanical parts such as motors, gears, cams, and nuts and bolts. They can in turn be integrated with found objects to create installations which interact with the physical world. These kits require programming on the computer to fully realize their potential as autonomous artificially intelligent objects. They provide the basic software and hardware for participants to engage in a process of discovery that leads to innovation in finding solutions to their engineering design based challenges. These kits are employed as tools for participants to discover, explore, and incorporate in their multi-disciplinary project-based challenges.

Multi-disciplinary program content designed to give participants the opportunity to explore a variety of STEM subjects included the following: a) Life Sciences - habitats and behaviors of the desert tortoise, Gopherus Agassizii, which is a protected species in Arizona; b) Sustainability - environmental, economic, and societal needs in an urban heat island, the city in the midst of a desert; renewable energy generation; c) Technology - Robotics hardware and software, data collection hardware, computational software, & the Internet; d) Mathematics - estimation, graphing, visualization of data; and e) Engineering - electrical, electronics, civil/structural, mechanical, and computer science/programming.

Participants

Project Sites

Four middle schools were identified in a large school district in the greater Phoenix area. School district personnel, including the Superintendent, Assistant Superintendent for Curriculum & Instruction, Director of Curriculum for Science, Mathematics, and Social Studies, Director of Research and Evaluation, and the District School Psychologist played a role in identifying the potential project sites. Site selection had to meet the NSF ITEST program objectives of targeting underrepresented populations in the STEM fields. From a pool of fourteen middle schools, the Principal Investigator and the District School Psychologist who served as the district's liaison to the project visited six sites, met with the school principals, administrative team, and science and mathematics lead teachers before selecting two sites. Site selection occurred based on school administrators and teachers stated interest, access to facilities for the after-school program, and expressed interest in continuing the program beyond the term of funding. Project school site demographics are noted in Tables 1, 2, and 3.

Table 1. Percent Enrolled by Sex and Project School Site

	Site A (n=1,234)	Site B (n=1,143)	Site C (n=1,029)	Site D (n=1,435)
Female	50%	45%	46%	49%
Male	50%	55%	54%	52%

Table 2. Percent Enrolled by Race/Ethnicity and Project School Site

	Site A (n=1,234)	Site B (n=1,143)	Site C (n=1,029)	Site D (n=1,435)
American Indian	9%	9%	1%	2%
Asian	2%	3%	1%	4%
Black	5%	6%	2%	4%
Hispanic	59%	70%	90%	24%
White	27%	13%	7%	66%

Table 3. Percent Eligible for School Nutrition Program and Project School Site

	Site A (n=1,234)	Site B (n=1,143)	Site C (n=1,029)	Site D (n=1,435)
Free lunch	57%	65%	75%	24%
Reduced-price lunch	14%	15%	12%	12%

Teachers

At each of the project sites, two teachers were identified to serve as after-school program facilitators. The principal investigator, the school district liaison to the project and the school administrator met with interested teachers individually and selected the two project facilitators for each site. Criteria for selection included expressed interest in the project curricula, curiosity and enthusiasm to explore new ideas and content, and availability for the duration of the yearround project. Teachers received a $3,000 stipend and seven professional development days when the district paid for a substitute teacher to work in the teacher's regular classroom.

Youth Participants

Table 4. Percent Project Participants by Sex and Year

	Number of Students		Combined	Percent by
	2007-08	2008-09	Sample	Gender
Female	32	35	67	58%
Male	16	33	49	42%
Total	48	68	116	

Table 5. Percent Project Participants by Race/Ethnicity and Year

	Number of Students		Combined	Percent by
	2007-08	2008-09	Sample	Race/Ethnicity
American Indian	4	1	5	4%
Asian	2	0	2	2%
Black	5	0	5	4%
Hispanic	25	46	71	61%
White	12	21	33	28%
Total	48	68	116	

Active recruitment generated applicants from each school site. A purposeful selection strategy was used to identify the 24-32 seventh grade students from each site who were asked to join the project. In 2007-08, cohort 1 started in sites A and B. In 2008-09, cohort 2 started in sites C and D. Student demographics are shown in Tables 4 and 5. Participant selection began with after-school program coordinators and district administrators identifying students who fit the following criteria: a) the student had successfully completed the sixth-grade state standards based exam in Mathematics and Language Arts; and b) the student had no major behavioral or criminal incidents on their record. The names of these potential students were separated into two lists, by school. Each individual list was forwarded to the corresponding school principal who then circulated the list among teachers for their input. Teachers were asked to make any appropriate modifications, which included adding students they believed were a good fit with the program. Each school principal invited students who were selected to assemble in the school auditorium where the principal investigator and the project coordinators presented an overview of the after-school program. At the conclusion of the presentation, application packets including: a) a letter of invitation addressed to the student; b) a form seeking information from students as to why they wanted to join this program; c) a letter to parents informing them about the program; d) parental permission form; and e) a child assent form were provided in both English and Spanish. After-school program coordinators, district administrators, and cooperating teachers selected project participants based on students' applications.

Project Team

The project team included nine university researchers and faculty with expertise in the areas of engineering (Materials Science and Engineering, Industrial Engineering, Computer Science and Engineering), sustainability, science education, mathematics education, earth and space science, geology, counseling psychology, instructional technology, and education research methods. Project staff included: a) a female teacher with ten-years of experience working with women in science and engineering who was also enrolled part-time in a master's degree in bio-engineering; and b) a male graduate research associate with a bachelor's degree in mechanical engineering and a master's degree in mathematics education who worked part-time as a high school mathematics teacher while also enrolled in a doctoral program in mathematics education. In addition, two undergraduate research intern's one for each school site, a male (Materials Science and Engineering) and a female (Electrical and Electronics Engineering) worked to help facilitate the project.

Project Activities

Project activities were separated into two sections: a) academic year activities and b) summer activities. Activities were offered for 78 contact hours during the academic year and for 48 contact hours during the summer. During the academic year, participants at each site met in their respective media centers for 90 minutes, twice a week. Weekly schedules were adapted to comply with field trips, district holidays, testing days, and half-days. Participants at the after-school program were provided with a healthy snack and a drink by the school.

Units delivered throughout the academic year comprised: a) Desert Tortoise - study and simulate desert tortoise behaviors using LEGO Mindstorms NXT robotics by building a toy that behaves like a desert tortoise; b) Circuits, Chain Reaction, Rube Goldberg Machines - study ideas of local actions and global reactions by building chain-reactions using PICO Cricket kits, found objects, and electrical circuit components; and c) Urban Heat Island - study the heat island phenomenon and build models to mitigate heat. Students were also afforded the opportunity to engage in fieldtrips, parent nights, and internships related to program content. Fieldtrips included a visit to the state zoo, visits to solid-state engineering, materials science, and sustainability labs, and the art museum at Arizona State University. During the summer, students experienced a youth docentship at the Arizona Science Center and an industry-internship with the Salt River Project, a local energy and water company.

Cognitive apprenticeships were provided through: a) undergraduate student interns from STEM programs in Mechanical and Aerospace, Electrical and Electronics, Materials Science and Engineering, Chemical Engineering, and Computer Science; b) active volunteers from industry partners in Boeing, Intel, Microchip, and Motorola; and c) local area and university professional engineering societies such as the Society of Women Engineers, Institute of Electrical and Electronics Engineers. These were aimed at providing participants direct access to individuals in various stages of STEM professions to confront stereotypes about professionals in these fields[28,54].

Students and parents attended four parent nights designed to give students an opportunity to share their learning. In addition to the four scheduled parent nights, two events specifically designed to elaborate on STEM education and career pathways information were offered. The first of these focused on eliciting students' notions of current career goals that were then juxtaposed against the multi-faceted aspects of engineering graduates (females and underrepresented populations). The second of these focused on different engineering fields. Students and parents explored *Engineering Go For It!: Make a Difference, Change the World*[55] with an interactive presentation from the facilitators. This activity introduced engineering as a human endeavor that is designed to meet human needs.

Desert Tortoise Unit

The charge to students was to design a simulation of a desert tortoise-the *Gopherus Agassizii*-[56] using technology (LEGO Mindstorms NXT software and hardware) and its habitat using found objects in an area on the school grounds. To accomplish this charge, students studied the behaviors and habitats of the desert tortoise. Students were afforded opportunities that allowed for engagement and exploration of the desert tortoise and the technologies. These opportunities provided environments where students could: a) interact with desert tortoises—baby and adult tortoises were brought to the after-school program; b) go on a field trip to visit a desert tortoise habitat at the Phoenix Zoo where the Sonoran desert is featured; c) meet and interact with experts, seek answers, and share ideas—a desert tortoise conservationist visited the after-school program with desert tortoises, and on the field trip to the local zoo, participants could interact with a herpetologist and a botanist; and d) explore the topic on their own with print materials (university research magazine focused on desert tortoise), the Phoenix Zoo's newsletter feature on the desert tortoise, children's books and poetry on the desert and desert animals[57,58], other resources from the state's Game and Fish Department, school and university libraries, and internet resources.

Students initially explored the LEGO Mindstorms NXT kits without the instruction manual so they could creatively explore the tools on their own before reviewing the instructions. This investigation process was followed by an introduction to the engineering design process, ultimately culminating in the design and construction of their desert tortoise simulation toys. Student learning was assessed using pre and post assessments, brief write-ups and sketches describing their designs, vocabulary word wall, project rubrics, white board presentations to peers, parents, and adult facilitators, and demonstrations of their simulations.

Circuits / Chain Reaction / Rube Goldberg Machine

Students were engaged with the idea of designing a chain reaction of their own after watching the "Cog" a 2003, Honda commercial. The "Cog" sequence begins with a transmission bearing rolling into a synchro-hub, which then triggers a series of movements such as the windscreen wipers 'walking' across the floor and valves rolling down a hood, etc. The song "Rapper's Delight" by The Sugarhill Gang plays in the background. After watching this two-minute sequence (some watched it more than once), students engaged in a free discussion on what they had seen and expressed that it was a "chain reaction." Notions of chain reactions such as local actions having global impact were discussed.

While students were engaged in creating their chain reaction components, other chain reaction videos were constantly looped and displayed on the screen. Students also had access to a variety of books that had designs of various Rube Goldberg machines. Students were provided with a variety of technology tools beginning with components for creating a simple circuit (switches, electrical cables, an light emitting diode-LED, buzzers, and a battery pack) and found objects (cardboard, coat hangers, aluminum foil, milk/juice cartons, etc). Students created circuits on their own using the provided materials and then progressed to making their own homemade switches using found objects.

PICO Cricket kits were introduced and students used the PICO software to program and design intelligent reactions to mechanical actions. Using PICO Cricket Kits students also created autonomous art installations that would respond to stimuli from their surroundings (e.g., sound, movement, touch, light). Some of these installations served as a table centerpiece for an event at Arizona State University where 200 STEM industry and community members came together with faculty, staff, and students, to celebrate the university's diversity of STEM programs.

Ultimately, the entire cohort, in teams of two students at a table, engaged in the creation and execution of a large-scale chain reaction or a Rube Goldberg Machine. Each table was joined to the next with one table designated as the starting point. Student learning was assessed using pre and post assessments; brief write-ups and sketches describing their circuit designs; project rubric, white board presentations to peers, parents, and facilitators; and demonstrations of their chain reaction creation.

Urban Heat Island Unit

Participants were engaged with the notion of the urban heat island phenomenon. An urban heat island is a metropolitan area like the greater Phoenix area that is significantly warmer than its surrounding rural areas. The main cause of the urban heat island is modification of the land surface by urban development. As the population around Phoenix has grown over the last 40 years at a remarkably fast rate, this growth has tended to modify a significant area of land around Maricopa County[59,60]. Based on the work of Elser, Musheno, and Saltz[61] we designed the Urban Heat Island unit. Over a six-week period, a staff member from the Global Institute of Sustainability facilitated this unit at the program sites.

Participants explored the urban heat island phenomenon by going on a field trip to Arizona State University's green building, to include exploration of various areas on the university's campus in the hopes of finding the best place for having lunch outdoors in mid-March 2008. Students measured and recorded humidity, temperature, and wind at designated locations on two allocated trails through the campus. Average measures were computed to use as discussion points for the group to determine the "best" location for lunch. In addition students interacted with graduate student experts who are studying the urban heat island phenomenon at the university's sustainability department in the green building. They engaged in a discussion on how the building is designed and what materials were used in its construction that contribute to keeping the building "cool" and maintaining low energy use. Students along with the graduate student experts engaged in measuring the temperature of different types of surfaces (grass, concrete, foam, metal, etc) and a solar energy panel experiment to generate energy. Students also explored print materials (e.g., the university's research magazine issue on Urban Ecology).

Following the field trip, students engaged in experiments on their own school campus to measure and compare the temperature of various surfaces (e.g., grass, soil, concrete, parking lot surface) in shaded and un-shaded areas. To account for variations, measurements were taken one inch and four feet above each surface. Temperatures were taken using indoor/outdoor thermometers and infrared thermometers.

Students used the experiences gained from their experiments to design and build a "room" using paper cups and cardboard boxes that could maintain the temperature of materials (e.g., water) in the room. Students were offered many different types of insulating materials (e.g., fiberfill, bubble wrap, gravel, Styrofoam) for use in their project. Student learning was assessed using pre-assessment, brief entries in student journals, and demonstrations of their designs.

Education & Career Pathways Activities

Students and parents were offered two education/career pathways workshops. The first of these focused on eliciting students' notions of current career goals that were then juxtaposed against the multi-faceted aspects of engineering student graduates (females and underrepresented populations). Undergraduate engineering student interns shared their journey to college and were available to answer questions from participants and their family members.

The second of these was facilitated by the principal investigator and featured the different engineering fields. Students and parents explored *Engineering Go For It!: Make a Difference, Change the World*[55] with an interactive presentation from the facilitators. The experience started with a review of images from the "Engineering Is…" sections (pp. 4-9) of the publication that was followed by whole group discussions with participants and family members. Participants focused on a chosen topic from the publication and engaged in a discussion of the topic with their family members. After-school program coordinators facilitated a discussion about what is engineering and how engineering impacts our daily lives. Undergraduate engineering students from a variety of majors made short presentations on their area of study and how their field impacts human lives. These undergraduate students acted as ambassadors of their field of study. They described how engineering and the sciences are relevant to their own interests and why they are pursuing their chosen education pathways. Participants and family members had the opportunity to ask questions and interact with the undergraduate engineering students. All participants were able to take a copy of the *Engineering Go For It!* magazine home with them to keep and explore at their leisure.

Various engineering and engineering-career content rich resources were introduced to participants and family members throughout the after-school program via short presentations and newsletters that were sent home. These included:
1. PBS Design Squad <http://pbskids.org/designsquad/>
2. Engineer Your Life <http://engineeryourlife.org/>
3. A Sightseer's Guide to Engineering <http://www.engineeringsights.org/>
4. Engineer Girl! <http://www.engineergirl.org/>

5. What is Engineering? <http://www.engineeringk12.org/students>
6. Greatest Engineering Achievements of 20^{th} Century < http://www.greatachievements.org/>

Arizona Science Center Youth Docentship

Participant youth had opportunities to explore the center's interactive exhibits, linked by themes relating to different aspects of science. Experiences included the following: a) hands-on exploration of energy creation by designing wind turbines; b) review of wind versus water uses for energy purposes; c) an exploration of the looming scarcity of fresh water supply and its uses via the IMAX movie *The Grand Canyon Adventure: River at Risk*—an exploration of global water issues; and d) interaction with the general public through shared activities in the center's Fabrication Lab. Shared activities consisted of participants demonstrating various scientific concepts to children and adults visiting the lab. Participants and family members had the opportunity on the final day of the youth docentship experience to explore the center on their own.

Salt River Project Powering our Future: Renewable Energy Summer Internship

This twenty-hour internship provided participants with the opportunity to interact with scientists and engineers who work at the local energy and water company. They learned about forms of renewable energy, the differences between passive and active energy technologies, and the impact of materials used in harnessing solar energy[62]. In addition, students engaged with hands-on explorations about natural resources, energy conservation, and renewable energy technologies. Participants visited the Salt River Project's facilities, observed a small-scale water energy generation center, interacted with professionals, explored careers in the energy conservation industries, and built working models to harness solar energy. They built solar energy modules in the form of solar ovens to cook food and tested their designs. They built arrays of photovoltaic cells to power a light bulb. On the last day of the program, parents attended an interactive showcase presentation of student work.

Data Analysis

Student learning was assessed using formal and informal methods. Informal assessments consisted of whiteboard presentations, open-ended questioning, student demonstrations, journal entries, and teacher observations. These informal assessment methods were used to guide daily activities and lessons, inform lesson plan revisions, and follow student progress. Formal assessments consisted of pre and post unit assessments and pre and post student-produced drawings. These formal assessment methods were used to identify student conceptions, student beliefs, and to track student progress.

Informal Assessment

The following tools were used for the facilitation and demonstration of student learning throughout the school year. Assessment was focused on learning what students know and are able to do[63,64].

Personal sized **white boards** and dry erase markers were provided to each team of two participants so they could record their ideas, sketches, and what they had learned. These ideas and sketches were then shared with peers during learning activities. They were also used for informal presentations to the adults—parents, teachers, and other visitors associated with the project. The personal sized white boards permitted participants to pass the white boards around to other teams. This facilitated easy exchange of ideas and knowledge.

Word walls were used at each program site and integrated into the project's learning activities. An interactive word wall was accessible for students to add any new and interesting words they had learned throughout the given unit of study. This tool helped enhance students' understanding of how words work as new vocabulary related to the STEM fields were visible not only for program participants, but also for other users and visitors of the media center (library and computer lab) where program activities were held.

Engineering notebooks were provided to each participant. Participants recorded their journal entries, sketches, designs, goals, personal questions, and organized materials such as resource handouts and information organizers in the notebook. We provided journal prompts to participants that served to facilitate: a) recording data collected during observations and field trips, b) information collected during content exploration activities essential for the project-based challenge, and c) reflection on the learning activities.

Formal Assessment

The Draw and Engineer (DAE) Assessment[65,66] was administered at the start and end of the program. The DAE assessment was given to determine individual preconceived conceptions of engineers and engineering. It is important to note that students in the study were given the pre-assessment during regular program times and the post-assessment during school as part of a school wide administration of the DAE assessment.

Students were given 30 minutes to draw an engineer and answer three questions related to what they had drawn. Assessment directions prompted students to, "Close your eyes and imagine an engineer at work … Open your eyes. On the attached sheet of paper, draw what you imagined. Once you have completed your drawing, please respond to the following prompts: a) Describe what the engineer is doing in the picture; b) List at least three words/phrases that come to mind when you think of this engineer; and c) What kinds of things do you think this engineer does on a typical day?" After-school program coordinators were careful not to talk about engineers or engineering during the initial presentation given to all students, during the first day of the program, or during assessment administration. During administration, after-school program coordinators offered help to clarify directions and question prompts, but they did not offer any ideas or assistance that would influence the students' original conceptions of engineers or engineering. Due to logistical constraints pre and post assessment data were only gathered for one of the two schools.

Table 6. Images in Project Participants' Drawing of an Engineer

N=103	Fix / Build / Labor	Fix / Drive / Train / Car /Plane	Fix / Build / Technical	Research / Study / Design / Invent	Observe / Test / Experiment
Pre	28%	37%	14%	31%	7%
Post	22%	27%	46%	41%	14%

Table 7. Images in Peers' Drawing of an Engineer

N=600	Fix / Build / Labor	Fix / Drive / Train / Car /Plane	Fix / Build / Technical	Research / Study / Design / Invent	Observe / Test / Experiment
Pre	20%	57%	9%	10%	3%
Post	24%	49%	21%	28%	9%

An open coding approach[67] was used to code the assessments. To begin the coding process drawings and question responses were examined for key elements describing engineers and engineering. In this section we will use the term *drawing* to represent both a student's drawing and their question responses. Once the researchers felt that all key elements had been identified in the drawing, they recorded a short memo describing possible concepts and general thoughts about the drawing. The process was repeated with all pre test drawings. Upon completion of the initial analysis, researchers organized and reviewed memos and key elements. The initial drawings were reviewed again using the complete list of key elements found during the first analysis. This process was continued until the researchers were satisfied that all key elements had been identified. The same process was used to analyze the post assessment drawings. Drawings from the post assessment were reviewed using the list of key elements generated by the pre test analysis. Again, memos and key elements were organized and reviewed. The final stage of the data analysis required researchers to review the entire set of pre and post assessment drawings using the complete list of key elements generated from the entire analyses. Review of the key elements and memos revealed three main descriptive categories: 1) fix or build labor; 2) fix or build technical; 3) fix or drive a train, car, or plane; 4) research, study, design, or invent; and 5) observe, test, or experiment. The percentage of participants' according to pre and post assessments as a function of all project and comparison students is shown in Tables 6 and 7.

Fix or Build Labor key elements depicted or discussed engineers working on an object, bent over an object, or seated holding an object with both hands. In this description an *object* refers to an item used in manual or factory labor; e.g. shovels, assembly lines, construction, etc.

Fix or Build Technical key elements depicted or discussed engineers working on a technical object, bent over a technical object, or seated holding a technical object with both hands. In this description a *technical object* refers to an item commonly seen in technological areas; e.g. computers, circuits, solar panels, etc.

Fix or Drive a Train, Car, or Plane key elements depicted or discussed engineers working on or driving a train, car, or plane.

Research, Study, Design, or Invent/Observe and the **Test or Experiment** key elements depicted or discussed engineers writing, reading, surrounded by components/gadgets, or surrounded by glassware. Indicators of reading and writing included: holding writing utensils, holding materials to write on, papers with writing, or books in plain sight. The deciding factor for distinguishing between these two different key elements was in the student's response to the open-ended questions. In most cases the drawing itself was not enough to distinguish between the two.

These data allude to a shift in the conception of engineers by both male and female participants. Before the students had experienced the curriculum designed for this after-school program the majority in both sexes conceived engineers as individuals who build or repaired mechanical apparatus. Upon completion of the first year there exists a shift from the engineer who builds to the engineer who thinks. Both sexes show an increase in the number of students who depicted engineers in less labor-intensive activities.

A large number of participants depicted engineers as people who fix things. Further analysis of participants' responses indicate that students described repair-type activities, such as repairing cars, car engines (auto mechanics) and plumbing—traditionally blue collar and male-dominated fields. Many students said that they have at least one family member, usually a male who works on cars in their home. The middle school grades are crucial for students' planning coursework in high school and developing potential career pathways. In this context, perceptions of engineers as auto mechanics—as persons who fix cars—can be (and is) discouraging to many, especially females, from considering engineering as a possible career.

We found that the preconceptions of engineers as "engineers work on engines" did change by the end of the year long project. Students' concepts about engineers expanded to include multiple engineering disciplines such as chemical, civil, and electronics engineering and depictions of a larger percentage of females (39%) as engineers. This change in perceptions of engineers can be attributed to project efforts that provided multiple opportunities for students to engage with volunteer engineers and undergraduate engineering students in both formal and informal settings. In addition, the use of the engineering design process in project activities and the activities themselves engaged students with the idea of engineering in a very broad sense.

Table 8. Pre-Post Assessment Statistics

Unit	Assessment	n	Mean	SD	Mean Difference	t	P
Desert Tortoise	Pre-Assessment	82	29.32	10.84	25.22	15.71	< .001
	Post-Assessment		54.54	12.86			
Circuits/Chain Reaction	Pre-Assessment	75	30.67	16.12	17.33	8.75	< .001
	Post-Assessment		48.00	14.57			
Urban Heat Island	Pre-Assessment	58	20.81	49.87	7.96	2.94	.005
	Post-Assessment		36.00	57.82			

Pre- and Post- Unit Assessments relating to content in each of the major units were administered throughout the program. Assessments consisted of 4-5 fill-in-the-blank questions and 1-2 open-ended questions. Assessments were analyzed to determine what impact the program had on student learning in related STEM content. Raw scores were converted into percent correct and two sample t-tests were conducted on the average score difference for each of the assessments: a) desert tortoise, b) circuits/chain reaction, and c) renewable energy summer internship units. The resulting statistics can be found in Table 8.

These statistical analyses show significant differences between the means for the pre- and post-assessments in all unit assessments; $t(81) = 15.71, p < .001$; $t(74) = 8.75, p < .001$; *and* $t(57) = 2.94, p = .005$. The analysis demonstrates that student participants in each unit (Desert Tortoise, Circuits/Chain Reaction, and Urban Heat Island) scored significantly higher on the post-assessment.

Points of View

The workplaces of today and tomorrow demand skills that are not merely exemplified as technological—logical, analytical, and technical, but also those represented as value skills—creativity, critical thinking, ability to see the big picture, and work with diverse learners[11]. These skills are essential in the development of future scientists, technologists, engineers, and mathematicians. Educational experiences within K-12 settings, colleges and universities need to engage learners in not only content knowledge, but also technological and value skills. The NSF[5] reported that current curricular approaches to engineering education appear outdated and de-contextualized. Students need to be exposed to inquiry-oriented learning environments[68] as a means of increasing their interest in STEM fields. The case for fundamentally changing how we introduce students to these fields and careers is strong.

This K-12 engineering education outreach and research program and its findings, underscore the need to enhance early STEM interest, through in-school and out-of-school experiences to influence academic choices, career options, and educational pathways.

Educational Importance of the Study

In 2004, a review of K-12 Engineering Education practices by the American Society for Engineering Education offered specific guidelines for future engineering education programs: a) hands-on learning—make the relevance of engineering to our social lives public and offer context-based education, b) interdisciplinary approach—include technology in all disciplines, and add writing to mathematics and science, c) standards—include engineering in curricula that map to state and national K-12 science and mathematics standards, d) engage K-12 teachers—in engineering outreach and writing of K-12 engineering curricula, e) make 'engineers' cool—reach out to females and urban schools and create more mentors, and f) partnerships—create incentives to include partners from industry and higher education in K-12 engineering education. The *Learning through Engineering Design & Practice* project has addressed each of these guidelines in this 2007-2010 effort, although only project year 1 (2007-08) activities and related research are reported in this paper.

The variety of assessments used in this project could potentially be useful to the educational community. Formal assessments do not have to be teacher-structured multiple-choice questions that serve only to limit student responses. In this effort we used structured and semi-structured pre and post assessments that permitted students to share what they know. In addition, the subject produced drawings as a form of assessment, permitted the student to visualize his or her response not only in their imagination, but also on paper. This is not to imply that this type of assessment technique is without its drawbacks. Limitations in this type of assessment do exist and they are directly related to participants' skill level in drawing. Care should be taken to design assessments that allow for a broad range of skills in making drawings. The potential for eliciting higher order thinking is limitless.

In addition, the project-based challenges allowed students to assess for themselves whether they had succeeded in meeting the challenge. The project itself is the product. We used rubrics to assess students' products that they created based on the engineering design process. The analysis of data collected through various other embedded assessments will be presented in a future research report. In the future we intend to collect data to analyze students' programming skills as it relates to how they create autonomous robots using the Lego Mindstorms NXT and the PICO Cricket kits in their project-based challenges.

We have discerned that by engaging youth in learning that emphasizes both utilitarian and inquiry-based motivations, where learning is made relevant to students' lives, the outcome leads to enhanced learning in content areas. We have also learned that systematic efforts are needed to dispel misunderstandings regarding STEM subjects and professions. Coordinated and carefully designed in-depth and long-term experiences are needed to provide students and families with knowledge of STEM education and career pathways. The critical issue for our nation is to enthuse all youth, particularly, traditionally under-represented students: *females and ethnic minorities*, in STEM subjects. Results from this study will be useful for others who are interested in informal learning strategies and studying the impact of such efforts.

Future directions for research in K-12 engineering education include the incorporation of model eliciting activities into such efforts[69]. The focus is on "eliciting from students conceptual models that they iteratively revise in problem-solving." If we want to facilitate experiences where students can be encouraged to confront misconceptions and promote discovery by encouraging problem solving in context, an understanding of how students develop their thinking when engaged with an engineering design challenge will be important to move the engineering-education research agenda forward.

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