# AC 2012-4121: FOUNDATIONS AND EFFECTIVENESS OF AN AFTER-SCHOOL ENGINEERING PROGRAM FOR MIDDLE SCHOOL STUDENTS

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# FOUNDATIONS AND EFFECTIVENESS OF AN AFTERSCHOOL ENGINEERING PROGRAM FOR MIDDLE SCHOOL STUDENTS

**Abstract**
Calls for improving Science, Technology, Engineering, and Mathematics (STEM) education in the United States are well-known and well-publicized. This attention has led to efforts to introduce engineering in the K-12 grades. While K-12 schools are just beginning to offer courses in engineering, informal, afterschool programs that focus on engineering have been available for a number of years. However, the effects of these afterschool programs are not as easily documented and are therefore not well-studied.

In this paper, we describe a novel afterschool engineering program targeted for middle school grades. The afterschool program builds on our many years of experience in conducting engineering-based professional development for K-12 teachers. The program is founded on a three-pronged approach of: 1) engaging students in inquiry-based learning opportunities that feature motivation of engineering concepts with readily-available technology examples, and team-based design projects with the *National Academy of Engineering 21st Century Grand Challenges* themes; 2) professional development and support for teachers to guide students in meaningful engineering design activities; and 3) informing parents and caregivers of the full range of STEM college and career pathway options so they can guide their students towards STEM-related educational choices.

We have evaluated our afterschool program using student surveys administered in the fall and spring semesters (e.g., before and after the programs), and conducting more in-depth focus groups. The findings from the initial evaluation indicate that students in the target grades throughout the school district exhibited an increasingly positive attitude toward engineering and science-related careers. Likewise, teachers who participated in the program noted positive changes in themselves that they translated into strategies for teaching in their classrooms.

## 1 Introduction

There is general agreement that Science, Technology, Engineering, and Mathematics (STEM) education in the United States is in a crisis, and innovative educational approaches are needed to address this crisis. The National Academies report describes this crisis and its effects on the nation's vitality and competitiveness in the modern global economy.[1] Although high-tech jobs requiring advanced STEM education expected to be the fastest-growing occupations in the 21st century[2], enrollment in post-secondary STEM curricula is decreasing. In our state, only about two percent of high school graduate receive engineering degrees. Clearly, strategies are needed to reverse this trend.

Engineering will play a critical role in addressing this crisis. Engineering figures prominently in the recently developed K-12 science education framework.[3] Several states have adopted or are considering adopting standards for pre-college engineering, and a number of off-the-shelf curricula are available for teaching pre-college engineering, particularly at the high school level. We believe that all students can benefit from exposure to design and engineering. Although not all students will become engineers, all will need problem-solving and negotiation experience, tolerance for ambiguity, an understanding of systems thinking, technological fluency, and STEM literacy.[4] Additionally, mastery of core subject material can be enhanced through engineering design, since it provides context for these subjects[5] and encourages generative learning.[6, 7, 8, 9, 10, 11] Engineering outreach programs have demonstrated increases in science and mathematics content learning.[12, 13, 14, 15] Some studies have shown increases in student achievement scores as well.[16] Other measures that allow students to demonstrate their ability to explain, analyze, predict or reason about science, mathematics, or technology content demonstrate that learning has indeed occurred and can be attributed to engineering activities.[17, 18, 19]

While improvements to STEM classroom instruction are necessary and important, and the introduction of engineering in the classroom is significant, success in addressing the STEM crisis hinges on getting students interested in STEM subjects. Engineers have a long history of sponsoring out-of-class programs aimed at piquing students' interest in engineering in particular, and STEM in general. Informal, afterschool programs that focus on engineering have been available for a number of years. [20, 21] However, the effects of these afterschool programs are not as easily documented and are therefore not as well-studied.

In this paper we describe an out-of-class program developed at The University of Texas at Austin (UT Austin) that includes afterschool and summer camp curricula based on our 20 years of conducting professional development in engineering for teachers. This program was adopted by a small school district in the Austin, TX, area for all three of their middle schools. The district has an exceptionally large population of high needs students. We present the results of our evaluation of the program, documenting increases in student interest in STEM education and careers. Additionally, we discuss the effects the program has had on the teachers involved in the program.

## 2 Program Description

Our program, *Beyond Blackboards*, offers an integrated approach to engaging middle school students, teachers, administrators, parents and caregivers in activities that improve awareness and understanding of a range of STEM college and career pathways. The program is framed within the *Grand Challenges of the 21st Century* identified by the National Academy of Engineering. *Beyond Blackboards* employs a three-pronged approach of: 1) engaging students in inquiry-based learning opportunities that encourage practice of key STEM concepts, development of analytical skills, and increased awareness of STEM college and career pathways; 2) professional development and support for teachers to guide students in meaningful engineering design activities and targeted STEM college and career pathway investigation in the context of after-school clubs and summer engineering camps; and 3) informing parents and caregivers of the full range of STEM college and career pathway options so that they may support and encourage their students' pursuit of STEM-related educational and professional goals. In our program, middle school teachers, who receive extensive professional development, conduct the afterschool clubs and summer camps. They are supported by UT Austin undergraduate students who act as mentors and role models for the students. Additional, industry mentors are recruited to provide technical support as well as STEM career information.

## 2.1 Underlying Principles of Our Curriculum

*Beyond Blackboards* is founded on design-based learning, which incorporates differentiated curricula with active learning. It is an instructional methodology in which students are engaged in solving socially-relevant community, regional, national, and global challenges. Our approach is based on a five step cycle that includes:

1. **Hands-On Technology Exploration** introducing a technical subject to participants through everyday examples, thereby providing opportunities for participants to identify science, mathematics, and engineering principles at work in their lives.
2. **Interactive Discussion** of the principles illustrated by the technology examples, which generates rich discourse concerning the underlying science and mathematics concepts.
3. **Exploratory Laboratories** that allow participants to investigate and test engineering principles in an inquiring manner, a crucial step in learning to solve design problems.
4. **Open-Ended Design Problems** that feature ideation, prototyping, and testing, allowing the participants to apply engineering content and problem solving skills.
5. **Reflection** in which participants gain experience communicating technical information by describing their design solutions, thinking and planning processes, teamwork, and how they used the engineering principles.

This approach is developed within a project-based learning (PBL) framework. PBL is a curriculum development and instructional approach, emphasizing student-centered instruction and the execution of projects as the focal learning activity. PBL has been shown to substantially improve long-term retention and "deep understanding," i.e., the ability to extrapolate knowledge to subsequent learning experiences and new situations.[22] Many studies have demonstrated the efficacy of PBL in science and mathematics, including grades K-12, as well as in legal, medical and engineering education.[23, 24, 25]

Our approach also aligns with the well-known Kolb model, which describes an entire cycle around which a learning experience progresses.[26] The goal is to structure design-based learning activities that will proceed completely around this cycle, providing the maximum opportunity for full comprehension. This model has been used extensively to evaluate and enhance engineering teaching.[27, 28]

The approach provides rich opportunities to embed active learning in the program, particularly with during the exploration, experimentation, and design problem solving stages of the process. Active learning approaches improve students' overall learning, a view shared generally by faculty in STEM education.[29] The foundation of active learning is a social constructivist teaching philosophy. This approach seeks to alter the mode of knowledge and conceptual understanding through active student construction of learning rather than passive reception. Active learning or interactive engagement does not comprise a single approach; rather, many approaches may be executed through a variety of modes and media.[30, 31, 32, 33, 34, 35, 36, 37, 38, 39] There is considerable literature that addresses the advantages of using active learning in STEM curricula.[29, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54] Students' motivation and learning are simultaneously enhanced by the incorporation of active learning and critical reflection into the classroom.

## 2.2 Curriculum Elements

We have chosen robotics technology, particularly LEGO® MINDSTORMS® NXT, as the vehicle for our out-of-class design challenges. This is a natural extension of our over 12 years experience teaching robotics and automation professional development workshops for K-12 teachers. LEGO® MINDSTORMS® offers particular advantages for afterschool design activities, as the product supports rapid construction of prototypes, which fosters iterative design solutions. Additionally, the programming aspect of robotics offers an engaging introduction to skills needed for success in information technology and other STEM fields. We have found this dual nature of robotics (hardware and software) accommodates the diverse interests of middle school students. Robotics technology has been shown to be an effective means of engaging students in meaningful design activities.[55] Although the nature of the platform often leads to "trial and error" design rather than systematic design, other researchers have used it to promote redesign with younger children and found that robotics offers multiple teaching and learning opportunities.[56]

During the academic year, middle school students meet for four hours per week in afterschool "Innovation Clubs". During the fall semester, the clubs register and prepare to compete in FIRST LEGO League's (FLL) international competition that incorporates robotics, design, and project-based learning based often times on a socially-relevant theme. The theme varies annually but always focuses on a complex issue of interest to society. For instance, recent themes have involved biomedical engineering (2010) and food production and distribution (2011). The clubs design build, and program robots to successfully navigate an obstacle course based on automation and control. They also research and present unique projects about an area of importance and interest related to the theme that impacts their local community. In addition to learning about and presenting research projects and robotics, students work on 21st century skill development because, embedded throughout the FLL experience, is an emphasis on core values such as team work.

Throughout the spring semester, the curriculum for the Innovation Clubs focuses on two *NAE 21st Century Grand Challenges* dealing with exploring alternative energy and restoring and improving urban infrastructure. During this time, students investigate solar and wind energy. The clubs continue to use the LEGO® MINDSTORMS® NXT robotics kits, augmented with other a technical resources. We integrate additional hardware, such as solar panels, wind turbines, and additional sensors, and teach ways to apply new software techniques as students evolve in their programming. Each of the design teams in the Innovation Clubs participates in their own open-ended design problem within the context of *"(Re)New Orleans",* based on a theme of restoring and improving infrastructure in the wake of a natural disaster. They design, build, and program robots to creatively solve issues of infrastructure and energy that deal with the preventative and reactionary measures needed for hurricanes. The design teams research and present their chosen design projects using multiple media to share their ideas and problem-solving strategies. Overall, students are identifying and seeking innovative solutions to some of our world's most pressing problems by designing engineering solutions.

The summer out-of-school program is a day camp that takes place over two four-day weeks and features semi-aquatic and fully submersible underwater remote-controlled robotics. Middle school and upper elementary school students address design challenges related to the *21st Century Engineering Grand Challenge* to provide access to fresh and clean drinking water. Students explore concepts of automation and control, remote control, and engineering fundamentals as they design, construct, and program robots for water environments. Each of the robots is designed with a mounted live-feed camera so that the robot can capture important information about the water environment. The students are charged with defining their own contexts and creating their own scenario and built environment within water throughout their engineering design-based learning. By researching, defining, and designing their own scenarios for their project, students identify and generate innovative solutions to issues that are most pressing and interesting to them. The camp is held on the UT Austin campus, and features a sleep-over in a dormitory the last night before the camp ends. This provides underrepresented students with the opportunity to experience the college environment personally. As a culminating event, families and caregivers, school district leaders, and industry are invited to the university campus to attend a celebration of the student design teams' presentations of their research and robots in action.

### 2.3 Professional Development

All of our teachers participate in a week-long summer professional development institute (PDI) to investigate engineering, design-based and project-based learning, robotics construction and programming, and other STEM areas. The PDI is designed to model the same five-step teaching method on which the curriculum is based. We emphasize the use of hands-on technology and design challenges to provide context for learning, including robotics as a primary manipulative. Our curriculum and professional development facilitates design experiences that directly relate to the *21$^{st}$ Century Engineering Grand Challenges* and integrates LEGO® MINDSTORMS® kits, household materials, toys, narratives, and videos as points of access into student learning.

During the academic year, we continue to support the teachers with professional development to hone their skills in understanding and integrating engineering concepts into their teaching and in project-based learning experiences. Feedback from the teachers indicates that they greatly benefit from these additional professional development opportunities and collaboration time together to most successfully implement the program. These are one-day professional development institutes that focus on programming pedagogies, design-based teaching and learning, and details of the curriculum and curriculum resources.

We also conducted one-day educational sessions for our undergraduate mentors. These undergraduate students learned about ways to mentor middle school students and to collaborate with teachers in engineering education. We recruit undergraduates from a range of backgrounds and majors to promote diversity. As such, mentors also learn about strategies for construction and programming of LEGO® MINDSTORMS® to provide technical assistance in afterschool clubs and summer camps. We have also used undergraduate students to assist in development of curriculum materials and to add their own ideas for enriching the curriculum.

### 2.4 Parent and Caregiver Involvement

An important component of our program is engagement of parents and caregivers in creating a culture of engineering and STEM education. Afterschool parent nights offer a number of opportunities for engaging caregivers in STEM exploration activities ranging from participating in discussions of engineering career and college pathways to attending team competitions that foster celebration of academics and learning. To take advantage of these events, we developed fun nights focused on STEM learning. In particular, a family learning event, called "Engineer-it", was provided at each middle school. The English-Spanish activities included hands-on activities in which parents/caregivers were encouraged to work with their middle school students and siblings to solve engineering problems. These activities included dissection of household appliances and a challenge to construct the highest structure from given materials. Develop and test a new family fun night that would use an entertaining approach to learning about school success and how families assure it. Another activity, called, "Steps to Success," is a board game that illustrates the steps and choices students and parents/caregivers must make for their students to have successful STEM-based academic careers.

Caregivers are also encouraged to join their students on local visits to industry and college campuses. For parents of under-served students, visiting a college campus for the first time may remove a barrier to encouraging their students to pursue higher studies.

We found that successful family activities require close coordination with family liaison staff person on each campus. For instance, we determined that the driving interests at the middle schools are not to raise parent interest in robotics programs at the school but rather to bring diverse populations together over STEM activities. We also discovered that many parents in the district – though not necessarily the parents who communicate with the school– are professional engineers representing many foreign countries and languages. Some families are only in this country for two years before returning to their home countries.

## 3 Evaluation

In the 2010-2011 school year, the program focused primarily on the middle school level in the district. The program served a total of 80 students who participated in afterschool clubs at district schools (from September 2010 to May 2011) and 50 students who participated in a 2-week summer camp hosted on the university campus in June 2011. Table 1 below presents the demographic information for the students in the school district, in the afterschool clubs, and in the summer camp.

Table 1. School and program demographic information.

| | **District-Wide Enrollment** | **Afterschool Club Participants (middle schools)** | **Summer Camp Participants (middle schools)** |
|---|---|---|---|
| No. of Students | 10,158 | 80* | 50 |
| % African-American | 12 | 14 | 26 |
| % Hispanic | 80 | 66 | 55 |
| % White | 7 | 18 | 16 |
| % Economically Disadvantaged | 85 | 76 | 61 |
| % Limited English Proficiency | 31 | 7 | 0 |
| % Female | 49 | 30 | 37 |

*The number of program students includes those who participated in the program at any point during the 2010-2011 school year, with a slightly larger number in the fall than in the spring semester.

As part of the evaluation component of the program, surveys were administered campus-wide twice in the 2010-2011 school year (in the spring and fall semesters respectively) at each of the middle schools. The surveys included questions regarding the students' attitudes toward and interest in science and engineering, their educational aspirations, their awareness of and participation in the afterschool clubs, and background information about their family and caregivers. The questionnaire also included items from the *Trends in International Mathematics* *and Science Study* (TIMSS) 2007 for 8th graders to compare these students with nationally representative students from the TIMSS sample.

In addition to middle school students (approximately 2,300 total respondents), the evaluation team administered surveys to students in the fourth and fifth grades (approximately 1600 respondents) as well as to educators in the district (approximately 350 respondents). To gather more in-depth information, the evaluation team also coordinated and conducted focus groups with program participants—both students and teachers—at the district middle schools. The student focus groups lasted about 30 minutes and were conducted at the students' schools. The teacher focus group was conducted at the end of a half-day professional development session. The focus group data provide detail on the results from the survey data collection.

This paper focuses on findings from the middle school level. In particular, the responses on the student surveys indicated a range of programmatic impact, and we discuss the most notable findings are presented. Information collected through focus groups is included as supplementary to the survey findings.

### 3.1 Perception of Engineering and Science-Related Careers

One of the most notable findings among middle school students concerns their attitude toward science-related careers:

- On average, 32% ($p < 0.001$) of students surveyed reported in the spring that they would like to be an engineer – a significant increase from 26% in the fall.
- Aspiration for a career as a scientist also significantly increased, from 24% in the fall to 27% ($p < 0.001$) in the spring.
- Among the participants in the afterschool clubs, the percentage of students with a positive attitude toward a career as an engineer increased from 47% to 60% ($p < 0.01$) from the fall to the spring.

A program teacher shared how, after the robotics competition in the fall, a participating student proudly proclaimed that "'I think I could do this as a job!' You're equating 'nerdiness' with 'coolness,' so you can see the transition from 'I don't want to be a nerd' to 'Oh, this is cool. I want to do this!'" Another teacher noted the effect of the program with a different example:

> My best girl has decided that she wants to pursue robotics. Her biggest disappointment is that she doesn't know if they have robotics at the high school level. But she's already caught; she's hooked. She's decided to go into engineering.

The survey results indicated significant differences between participants and non-participants with regard to a positive effect and understanding about engineering and engineering careers. The two groups were statistically similar in the fall, but not in the spring, in enjoying learning how things work (90% and 85% in the fall compared to 91% and 79% in the spring, $p < 0.001$, for participants and for non-participants respectively) and in understanding that engineers work with others in groups (74% and 79% in the fall compared to 64% and 83% in the spring, for participants and for non-participants respectively, $p < 0.001$).

In summary, students' their positive attitudes about careers in engineering and science increased dramatically, district-wide. During the school year, program participants also increased their appreciation for and understanding of engineering careers.

### 3.2 Outlook in Educational Achievement

A majority (62%) of middle school students in the district have parents who did not attend college. The program participants did not differ from the overall population of the district in terms of their background; however, those who took part in the program showed impressive refocusing of educational expectations over the school year. The program participants decreased in uncertainly regarding their ultimate educational attainment and increased in their expectation to complete a bachelor's degree or higher. While non-participants experienced little change, the percentage of program participants who reported expecting to finish a four-year degree increased from 19% (fall) to 40% (spring) and the percentage who reported not knowing how far they expect to go in school dropped from 19% (fall) to 5% (spring).

Among the program participants, many noted how their experience in the program helped to direct their school learning. Concerning schoolwork in general, for example, one student noted, "[The program] makes me want to keep my grades up, so I can do robotics and not do summer school. So I can go to the summer camp [rather than having to attend summer school for remediation]." During the focus groups, many students shared how their interest and performance in the subject of mathematics had intensified. One 8th-grade female student observed, "I got better at math. The mentors (from the university) talk about rotation and distance of things. I'm in a regular math class, but I have a 100…Next year, I'm taking algebra." The experience with programming also influenced course-taking for some, such as enrollment in the "Gateway to Technology" class. Several students also perceived the program participation as facilitating their entry to college, through augmentation to their résumés and competitiveness in scholarship opportunities.

An additional student-reported impact from the program concerned persistence and skills in problem-solving. Many noted how they "never give up" but "keep on trying to make it work." Enjoying "the trial and error process" to make programming work, a student shared, "I learned to not say I can't because one of the [teachers] told me not to give up. So, I don't give up now!" Another student perceived that her better ability in "figuring things out" helped her "focus more in school…[like] with answering questions."

### 3.3 Impact on Teachers' Instruction

In addition to their observations on student accomplishments, the program teachers perceived positive changes in themselves, which had also transferred to their regular instruction, particularly with regard to approaches to and content in their regular instruction. One teacher observed:

> If I had my wish, I would teach…through robotics. It teaches every possible skill they need to know: how to research, identify problems, teamwork. I say to my fellow teachers all the time, "They need an emotional hook to their learning. If they don't have an interest in going to higher level places, they won't go there." Robotics provides all of this. We need to take robotics and make it an integral part of the entire school experience…Project-based [is] a better way of teaching.

A second teacher stated:

> I've become a little more hands-off. I had gotten in the habit of wanting things 1, 2, 3. I know that this has made me more comfortably to be able to say, "You know what? Try it." With the robotics, I can now say, "I don't know. Let's try it and see."

A third teacher noted:

> I've been bringing up the social issues that come with [the FIRST LEGO League]. "Well, guys, how do you think that they get medicine or water? How do they provide that?" We can talk about infrastructure, and I can give perspectives from an engineering point of view. So when we're looking at Third-World nations, we can look at other issues. Not just, "This is the capital of such and such country."

### 3.4 Attraction and Obstacles to Participation

When asked about the reasons for their involvement in the program, 79% of the students indicated that they participated because they like building things and that they thought it was fun, 71% enjoyed designing and working with robots, 61% liked the robotics competition, and 56% participated because their friends were interested. Focus groups conducted with program students confirmed most of the reasons for participation. Many also suggested someone in the STEM field piqued their interest in the program:

"My dad is learning to be an engineer, and I really wanted to learn."

"I know an aerospace engineer, and I wanted to become one."

"I talked to my mom. I have an uncle who is an engineer. I've seen what he does, and I'm really interested in engineering. She said that robotics is kind of the same thing. I said I'd like to join."

The students' decision to participate further developed into enthusiasm about the program. "Once you get the ball rolling and the kids come consistently, they enjoy it so much. You can see it in their faces," noted a teacher. During the focus groups, many students observed how "it's too short" and expressed wanting to have longer or more frequent program meetings.

While the non-participants overall demonstrated a lower level of enthusiasm for robots, additional barriers were reported as keeping them from participating. For instance, 47% shared that they were too busy with other activities, 44% had to be home before it gets dark, and 43% needed to help at home after school.

## 4 Conclusion

Improving STEM education is a national initiative that this program is actively committed to addressing. The *Beyond Blackboards* model is based on a comprehensive community approach that integrates informal, out-of-school, design-based learning experiences to inspire diverse middle school students to advance in STEM courses and fields. We find that our three-pronged approach fosters a strong community culture of understanding and supporting engineering education. From afterschool Innovation Clubs to hosting an FLL competition to family 'Engineer It' nights to underwater summer camp on campus, our program impacted and improved STEM interest and self-efficacy not only for participating students, but also for students across all of the middle school campuses, as well as for the teachers too. The combination of contextualizing the curriculum with the *NAE 21st Century Grand Challenges* and design-based learning pedagogy resonated with the program participants who now show an understanding of the importance in engineering to solve pressing social problems. We continue to evolve the program elements in an effort to enrich engineering education and highlight ways to engage traditionally underrepresented groups in being inspired and prepared to become college bound and career ready.

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