Robotics-based Engineering Approaches in the G4-12 Curriculum

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1. Introduction

The modern workplace increasingly seeks people with engineering skills to understand and use model-based approaches, to interpret data and critically analyze situations, and to develop and refine models to solve problems. Recognition of such skills can be found in the Next Generation of Science Standards (NGSS) that emphasizes linkages between science and engineering. There is a need at the K-12 level for hands-on experiential activities to develop engineering, science, mathematics, coding, and innovation skills leading to the ability to think creatively and solve problems. We report on the development and implementation of a program that implements hands on activities to develop these skills at the elementary and early middle school levels.

Research shows that decisions to pursue STEM in later careers are influenced by early exposure during K-12 education [1]. This early exposure is also useful in understanding connections between coursework related to mathematics, science, and liberal arts. For example, a pilot study found that students who were introduced to neuroscience in the context of health sciences possessed an increased knowledge and awareness of the growing concerns related to mental health issues [2]. Another study found that students who pursued higher education in STEM reported having an early personal connection to their field through a family member or friend with a career in STEM [3]. Students who lack such personal connections may also be drawn to the field by shadowing a researcher or listening to a presentation of their work [4]. While the challenges of incorporating STEM into the classroom persist, the availability of inexpensive classroom resources have increased substantially in the past decade. The increase in availability and the reduction in the number and cost of necessary experimental materials [5],[6], allows educators to develop smaller-scale experiments more easily now than ever. While there are ample resources for STEM education available, the problem for teachers lies in finding ready-made materials to use, incorporating them into the classroom, and acquiring training in their usage.

A promising approach for linking science and engineering is providing design challenges that use Lego robotics with sensors, coding, and communication technologies such as Bluetooth. At the University of Missouri, we have been promoting such an approach in schools state-wide [7]. The year-long program includes 1.5 hour weekly after-school activity that begins every session with a math-drill which is followed by a series of learning activities that include basics of sensors, coding, and robot construction. After the lessons, students are presented with simple Lego robot design challenges. Another consideration in structuring the activities is to prepare the students for the annual Robotics Design Challenge that has been conducted at our University since 2006. The program also uses a comparative theme of human (brain/body) and artificial (Lego) robotics that enhances motivation for learning via personal and real-world linkages. In the process, students also recognize the parallels between how our brain integrates sensory information to control our muscles and how a computer integrates information from its sensors to control the robot.

Such linkages permit seamless introduction of important electrical and computer science concepts such as programming, math, system integration, and design concepts and also fosters motivation for STEM learning in a team-based social setting. Such connections are of interest to teachers in our group because the new NGSS standards require that educators integrate both engineering and neuroscience concepts into the K-12 curriculum.

We report results from our Lego-robotics program administered to 4th, 5th, and 6th grade students over a period of two years in several school districts across Missouri. We surveyed 129 students with pre- and post-instruments. We found that students reported high positive attitudes toward math and science. Males and females did not differ in attitudes toward math and science. To assist teachers with understanding the relatively new engineering and science standards, we are adding specific standards to the curricula. We provide such an overview of standards below for both engineering and neuroscience. We also note that the comparative theme of human (brain/body) and artificial (Lego) robotics used in the curriculum is not only interdisciplinary and engaging, but also enables inclusion of science, mathematics, engineering, and life sciences K-12 standards in an integrated manner.

2. Engineering Provides an Ideal Setting to Emphasize Design and Integrate STEM Concepts

The implementation of engineering and technology into schooling has a long history starting with the formation of the American Industrial Arts in 1939, which later evolved into the International Technology and Engineering Educators Association (ITEEA [5]). Although the ITEEA has been developing engineering and technology curricula since the 1960s, the formal standards for technological literacy were launched only in 2000. Since then the K-12 curriculum has been based on these standards, plus the national standards for math and science, Common Core, and NAE's grand challenges for engineering [6]. We first provide a brief history of how various groups have been proposing standards and curricula in engineering (including universities, corporations, museums, etc. with funding from federal sources) which seem to have finally coalesced by into a common set of standards with the creation of NGSS by the US states with a motto 'by states for states.' Understanding the evolution of engineering and technology standards is instructive as administrators incorporate NGSS standards related to engineering across their K-12 curriculum in almost all states, since few have had such standards. Similar implementation issues would also be relevant for the new NGSS standards related to neuroscience.

<u>Engineering standards – a brief history</u>.
Before NGSS incorporated engineering standards into its curriculum, there were many outreach programs and summer camps created by universities and companies that offered engineering instruction to K-12 students, with the goal of meeting the national and industrial need for more high quality engineers [7, 8]. Brophy et al. [8] reviewed a number of these and included a table of the programs. The format of these early programs was inspired by programs in Australia and the United Kingdom. Specifically, the focus was on engineering design and teaching the process by which engineers iteratively evaluate and solve problems. In the United States, this included several programs like Engineering is Elementary, which was developed by the Boston Museum of Science and included readings in engineering topics and projects consisting of design

problems. For elementary grades, the LEGO engineering program was developed by the Tufts Center for Engineering Educational Outreach and had a design focus. For middle and high school, there were programs like those offered by Project Lead the Way, the Infinity Project, and the modular Vanderbilt Instruction in Biomedical Engineering for Secondary Science, which based its curriculum on an iterative learning process [2]. Many institutions like ASEE had developed guidelines for engineering curriculum, but not until 2013 were there any national standards for engineering. Currently, twenty states have adopted NGSS and twenty-four have adopted standards based on the National Research Council Framework for K-12 Science Education [9].

Table 1 provides a summary of the standards movement.

Table 1. History of Standards: Significant events related to STEM standards
• 1989 publication of 'A Nation at Risk' by the National Commission on Excellence in Education (NCEE)
• 1985 the Carnegie Foundation for the Advancement of Teaching reported that US corporations were spending about 40 billion dollars on remedial education and professional development
• 1989 education summit with all 50 governors led to the creation of national education goals called 'Goals'
• 1989 National Council of Teachers of Mathematics published standards called 'Evaluation Standards for School Mathematics'
• 1994 Elementary and Secondary Education Act was passed to increase rigor in coursework
• 1996 The National Science Education Standards (NSES)
• 2000 Standard for Technological Literacy (ITEEA)
• 2001 No Child Left Behind Act was passed
• 2013 NGSS was created
• 2015 Every Student Succeeds Act passed

We next describe briefly the growing emphasis on neuroscience standards in K-12 advocated by the Society for Neuroscience [10], which aligns with NGSS. An innovative start-up company Backyard Brain is spearheading efforts to introduce low-cost neuroscience kits to K-12 schools and to 'democratize neuroscience' [11].

<u>The new neuroscience standards</u>.
NGSS has many topics that fall under the domain of neuroscience. For example, the Life Sciences standards (LS).A emphasizes the relationship between structure and function, and LS1.D highlights the importance of how the brain senses and interacts with its environment. The Engineering, Technology and the Application of Science (ETS) standards such as ETS-1 and ETS-4 align with engineering processes, including modeling systems [12], which is useful in the general approach to 'reverse engineering the brain', one of the 'grand challenges' put forward by the National Academy of Engineering [13]. Other standards that fall under the domain of neuroscience include those that also guide anatomy and physiology. For example, Foundation standard 1.1.2 g of the National Health Science Standards highlights the need to cover basic nervous system structure and function. Curriculum provided by Backyard Brains is also carefully being aligned with NGSS [12].

In summary, there will be numerous challenges, administrative as well as curricular, as the new NGSS standards related to engineering and neuroscience are incorporated into K-12 education at several levels. Our experience suggests that Lego robotics is one vehicle that is well-suited to address engineering curricular needs as we describe next.

3. An Innovative After-School Lego-Robotics Program

TECH4K-5 [7] is another long-standing program we have offered in parallel with the Lego camps cited above. It is an after-school program for elementary youth (4th and 5th grades) focusing on enlivening math and science by using engineering. The program utilizes a comparative theme of 'neuro-LEGO robotics' cited above which the students find very engaging. The free program provides interested elementary schools with Lego-robotics kits and instruction to initiate TECH4K-5 after-school programs.

The year-long program (Sept-April) started in 2009 and is open to rural and Title1 elementary schools across Missouri. The application form involves commitment from the teachers and school principal to host the program locally with kits and teacher/mentor support provided by our university. The program has to date involved 12 Title1 and rural schools across the state of Missouri. Graduate and undergraduate students team up with a science and/or math teacher in the school and a local mentor, and train them in how to conduct 1.5 hr/week after-school sessions for up to 25 students from grades 4 and 5. Teachers and mentors are provided year-round support as needed. The lesson plans and activities are developed with the intent that the participating teachers will use them later in regular elementary classrooms.

The curriculum used in the after-school program was developed by our Neural Engineering Lab and provided as PowerPoints and pdfs. The typical program used by the teachers is shown in Table 2. Lessons and activities were related to engineering and neuroscience concepts, with many aligned to NGSS and Missouri Science standards [12, 14]. Each week began with a 5–10-minute math drill which increased in difficulty throughout the program. Students were divided into groups and instructed to build the Lego robot. The first lessons were focused on kinematics; students were taught the concepts of radius and diameter and instructed to use this information to precisely compute the number of rotations required to move the robot to a prespecified location. [NGSS 3-PS2-2]. The next lessons were focused on sensors and made to relate to neuroscience concepts. For example, the robot's touch sensor was presented as analogous to the human sensation of touch; this was demonstrated as an exercise in which a student was instructed to close their eyes to walk forward until they sensed the wall with their extended arm. Other lessons about sensors included the basic operation of the ultrasonic sensor, which was related to how bats navigate their environments. This lesson also includes instruction about the basic concepts of frequency and the use of signals for communication. [NGSS PS4.C]

Several foundational topics in computer science were also covered; some of these are listed together with computer science performance standards. In a maze-solving task, the curriculum includes an introduction to flow control, explaining the basics of the 'wait for' instruction [3-5 AP.C.01]. Students worked in groups to develop an algorithm that solves the maze [AP.PD.01].

In this stage, they could test their program on the maze, assess what went wrong, and change their program [NGSS MS-ETS1-4].

Teachers are also provided with peer-reviewed curricular units (mentioned in an earlier section; hosted at the TeachEngineering.org site [15]) so that they can be used during these sessions or as self-learning tools by interested students and teachers. All the curricula also have relevant standards related to math, science, engineering, and technology.

Table 2. Typical TECH4K5 Curriculum by Week

Week	Activity during the 1.5-hour session
1	Interest Inventory – ice breaker, getting-to-know each other
2	Become familiar with LEGO EV3 kits, begin to build basic robot
3	Continue building basic robot
4	Use Bluetooth to remotely control the robot. Teachers explain that robots will soon be programmed to move.
5	Introduction to the EV3 programming environment.
6	Students program robot to go forward a certain distance. Teachers help students calculate how number of wheel rotations translates to distance travelled.
7	Students try to program robot to navigate a simple obstacle course using only motor commands.
8	Students continue to program using only motor commands. Teacher explains this is like trying to walk without ears or eyes.
9	Introduction to the sensors.
10	Students program using the touch sensor – make the robot go forward until it hits an object then stop.
11	Continue with the touch sensor challenge
12	Introduce other sensors
13	Students learn to use the ultrasonic and light sensor to navigate obstacle course
14	Fine tuning of programs to complete the Design Challenge course
15	Robotics Design Challenge competition at our University

SURVEY RESULTS

Survey Methods and Questions.

The afterschool program was instituted in 8 different elementary and middle schools in the state of Missouri. Students were surveyed via Qualtrics at the beginning of the program with a pre-survey (n=325) and at the end with a post-survey (n=129). We analyzed data for the students for whom we had a pre-test and a post-test. There were 34 students in grade 3, 36 in grade 4, 49 in grade 5, and 10 in grade 6. They were 61 male students and 68 females. The students self-reported as 118 white, 3 American Indian or Alaska native, and 7 Other. 95% of the students came from Title 1 schools, which are schools that receive federal funds due to high concentrations of poverty. 75% of the students came from schools that were Title 1 *and* rural. One study showed that for the majority of students who end up pursuing STEM careers, interest in science for both males and females begins before middle school [16]; thus, it is important to begin early. A study using nationally representative longitudinal data found that eighth graders who intended to pursue STEM careers did so at high rates than other students [17]. The authors concluded that "to attract students into the sciences and engineering, we should pay close attention to children's early exposure to science at the middle and even younger grades" (p. 1144).

The survey consisted of 44 items that included demographics and questions about attitudes toward math and science. All the attitude items were on a 5-point scale. Being with friends is very important for students in grades 3-6, so we were curious whether students participated in the program to be with friends. The mean at pre-test was 2.8 and at post-test was 2.4 where 3 meant it was somewhat true that they went to be with friends (see Table 2). Thus, we concluded that students did not primarily attend for social reasons, and the rating of this social reason declined significantly ($p<.01$). One possible reason for the decline could be that when signing up for the program, being with friends is somewhat important, but as times goes on, the interesting activity becomes the main reason for participation and friends become less important; however, we don't have data that supports this interpretation.

Sex Differences. We averaged the following three items to create a very broad measure of knowledge of neuroscience: I know how a computer works, I know what a computer program is, and I know how my brain helps me move my hand. At pretest, girls reported significantly greater knowledge than boys ($t=-2.2$, $df=128$, $p=.04$) (See Table 2). We used three items to measure science attitudes and the same three for math attitudes (I like learning about science [math]). At pretest, males and females did not differ. (See Table 2.)

Self-efficacy refers to the confidence that one can carry out some action and is important for predicting interest, motivation, and goal setting. People with greater self-efficacy tend to be more interested, more highly motivated, and more likely to set and achieve relevant goals [18]. We used three items to measure science self-efficacy and the same three for math self-efficacy (e.g., even if science [math] is hard, I can learn it). At pretest, males and females did not differ. (See Table 2.)

Table 2. Mean ratings of variables at pre-test (5-point scale) for males and females (two-tailed independent t-tests)

	Means (SD in parentheses)		*t*
	Male	Female	(df=127)
1. Knowledge of neuroscience (3 items)	4.11 (1.00)	4.41 (0.63)	-2.01 *
2. Attitude toward science (3 items)	4.16 (0.94)	4.18 (0.83)	-0.10
3. Attitude toward math (3 items)	4.16 (1.18)	4.18 (1.18)	-0.12
4. Science self-efficacy (3 items)	4.2 (0.96)	4.3 (0.71)	-0.71
5. Math self-efficacy (3 items)	4.43 (0.78)	4.57 (0.61)	-1.20

Note: * $p < .05$; ** $p < .01$

Change Over Time. We wanted to know whether attitudes changed over time, so we used paired t-tests. As shown in Table 3, interest in and attitudes toward math and science did not change statistically significantly over the course of the program. It is noteworthy that students rated their attitudes as highly positive toward math and science at pretest, so there was not much room for an increase. Liking of the program declined, but that is not surprising because it is common for achievement motivation for school topics to go down over time [19], and it is logical that the same pattern would exist for an instructional after-school program.

Table 3. Mean ratings of attitudes at pre- and post-test (5-point scale) with paired t-tests (two-tailed)

	Means (SD in parentheses)		*t*
	Pre	Post	(df=128)
1. Interest in a science career (1 item)	2.95 (1.39)	2.85 (1.37)	0.90
2. Interest in a math career (1 item)	3.27 (1.47)	3.43 (1.42)	-1.47
3. Attitude toward science (3 items)	4.16 (0.88)	4.14 (0.88)	0.39
4. Attitude toward math (3 items)	4.17 (1.17)	4.11 (1.14)	0.71
5. Science self-efficacy (3 items)	4.27 (0.83)	4.32 (0.89)	-0.65
6. Math self-efficacy (3 items)	4.50 (0.70)	4.48 (0.82)	0.27
7. Perceived science ability (2 items)	3.76 (0.97)	3.93 (0.99)	-1.90
8. Perceived math ability (2 items)	4.26 (0.89)	4.22 (0.99)	0.46
9. Perceived value of science (2 items)	4.14 (0.96)	4.18 (0.90)	-0.56
10. Perceived value of math (2 items)	4.50 (0.82)	4.61 (0.75)	-1.31
11. Liking of the afterschool program (3 items)	4.67 (0.64)	4.43 (0.89)	3.10**
12. I go to the afterschool program to be with friends (1 item)	2.83 (1.54)	2.41 (1.51)	2.8**

Note: * $p < .05$; ** $p < .01$

We were interested in whether schools varied in their motivational impact, so we used one-way analysis of variance to compare the eight schools. While there were statistically significant differences in certain variables, they did not follow a discernible pattern. The variations in number of participants at each school (5 to 49) and the variations in the patterns of attitudes prevented us from drawing any conclusions. We did not see a consistent pattern of certain schools having high or low attitudes in the students.

<u>Change in math ability over time</u>.
Although the perceived change in math ability as reported by the students did not change significantly with time, we noted a significant increase in scores on math drills conducted every session (total ~15) over the course of the year. As we had noted, each after-school session begins with a math drill (5-10 minutes). The drill includes multi-digit multiplication and division and word problems, increasing in computational complexity throughout the program. Most teachers then scored the math drills and recorded them for each student. The records received from three of the schools showed consistent increase in math scores across the program, with Fig. 1 showing the increase in math scores with time for students (dots represents individual student) from three of the schools. All schools show an increase in math performance over time on the drills, with the largest increase being 67% for Mountain Grove Elementary. While we do not have objective evidence that the drills increased in difficulty, which would make the increase in scores even more impressive, the teachers reported that they created the drills with increasing difficulty.

Teachers devised ways of making the drills interesting for the students, including making on-line quizlets. Here is how one teacher reported the experience with math drills: “They did not enjoy the paper and pencil ones. So, after the first week, I took the problems and put them on quizlet online and had them use zzish to answer them. This allowed them to check their answers and then do the ones they got wrong over again. Doing the same problems but in this format made the kids enjoy the math drills a lot more.” All these findings are significant from an engineering perspective. The fact that math is not liked by students in known. So, the challenge for the educators is to incorporate math into Lego-robotics so that students enjoy the math and want to use math knowledge in ‘challenges.’ For example, the program has an activity where students need to calculate rotations of the wheel for the robot to traverse a certain distance. Such design challenges provide an opportunity for youth to learn how math may be applied in the real world. It is important to note that the math scores improved consistently for all three schools that provided the data to us so far. These data are continuing to be analyzed presently for finer insights.

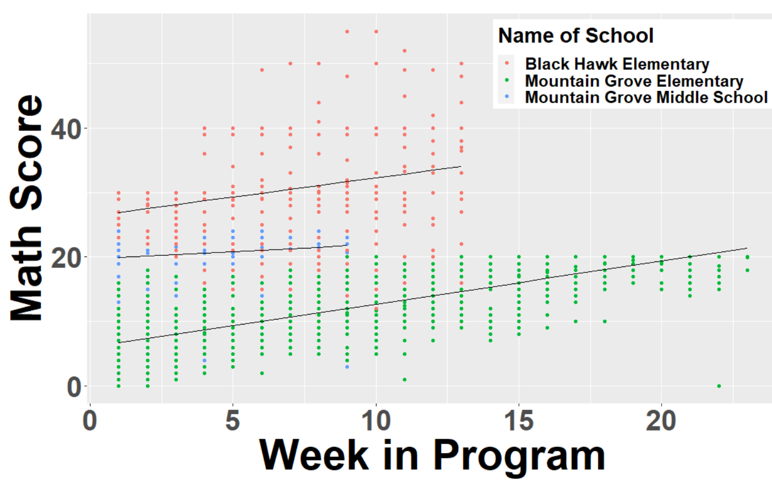

Figure 1. Math scores on weekly drills through the span of the yearly program

4. Future Directions

Powered by engineering and computer science concepts, a comparative theme of artificial and natural (human/brain) robot systems has been used to develop an interdisciplinary and engaging after-school Lego-robotics program. A total of 12 rural and title-1 schools across the state have participated, to date, in the long-standing program. We report details related to the program and results from a survey. The ongoing pandemic prevented us from offering the program during the past year and from gathering additional data. It seems likely that this early exposure to neuroscience concepts in the context of fun problem-solving activities will foster interest in the young participants. Lego robotics can be an effective medium for teaching basic versions of advanced concepts. We are presently developing lessons and activities focused on two topics: (1) control engineering concepts for K-12 and (2) neuroscience/neural engineering concepts; lessons will highlight linkages between the two. These lessons will be made available publicly, including via the site TeachEnginering.org, and piloted in schools across the state.

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