The Power of Educational Robotics as an Integrated STEM Learning Experience in Teacher Preparation Programs

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The use of integrated science, technology, engineering and mathematics (STEM) instruction has the affordances of combining harmonious content area connections into real-world experiences that are both engaging and challenging. This article introduces findings from a study that used an integrated robotics module to expose in-service and preservice teachers to the engineering design process, programming, mathematical connections and context, and problem-based learning. With participants ranging from novice to advanced user, this integrated module proved that given the appropriate scaffolding, anyone can successfully program a robot and have fun while engaging in STEM learning along the way. Implications lead to the conclusion that teacher preparation programs should integrate activities such as this to better equip teachers to engage students in the wonders of STEM in their own classrooms.

The United States needs more professionals with undergraduate and graduate degrees in the science, technology, engineering and mathematics (STEM) fields to serve as STEM professionals and STEM teachers. However, according to the International Association for the Evaluation of Educational Achievement (2011), U.S. students enter high school less well prepared in mathematics and science than students in other industrialized nations, a situation that is exacerbated by the shortage of well-prepared science and mathematics teachers. In answer to this need, states have increased efforts to define more effective K–12 learning standards. They have also recognized the need to focus on the combined content knowledge, skills, and habits that students must possess to be successful in postsecondary education or training. This is defined by Conley (2007) as "college and career readiness." Texas, for example, became the first state to mandate the development and use of college and career readiness standards as part of a P–16 continuum. In addition to revising content standards, this initiative led to the development of a set of cross-disciplinary standards that directs attention to strengthening foundational skills such as reading and writing across the content areas, analyzing data, and conducting research. These standards also support cognitive skill development such as reasoning, argumentation, and problem solving (Texas Higher Education Coordinating Board, 2008). In the meantime, 26 states convened in 2011–2013 to design more rigorous standards in science, with 11 of those states now having officially adopted a common set of science standards called the *Next Generation Science Standards* (NGSS; Hunt Institute, 2014). These standards (NGSS Lead States, 2013) bring inquiry and practice together and directly include content and practice ideas from engineering, even at the K–6 student learning levels.

The President's Council of Advisors on Science and Technology (2010) report on K–12 STEM education concluded that to prepare and inspire K–12 students in STEM, the United States should invest in teacher preparation programs that delivered strong content knowledge preparation, pedagogical training, and induction support to teachers. Preservice teachers deserve the opportunity to develop as professionals with strong pedagogical content knowledge in science and mathematics. Preservice experiences that integrate STEM will allow teachers to learn firsthand what content their students experience. This in-depth vertical knowledge will allow teachers to maximize curricular continuity for students and to better scaffold their instruction to build on what has been previously learned by students. Further, teachers will be able to intentionally design their instruction to integrate and reinforce the interconnections that exist between science, mathematics and engineering, supported by various technologies such as educational robotics. The instructional approaches in such preservice professional learning experiences include inquiry, active learning, reflective journaling, differentiating instruction, and making real-world connections using new technology aids such as educational robotics. As teachers at all levels begin to integrate these approaches into their teaching, it can be expected that student proficiency will also increase.

Educational robotics

Educational robotics is a specific application of K–12 engineering education and offers students physical manipulatives that are familiar and easy to work with as they participate in the engineering design process. In addition, students have many opportunities for use of the accompanying programming language elements that allow them to test variable settings and receive immediate feedback. Although educational robotics platforms such as LEGO Mindstorms, Sea Mate remotely operated vehicles (ROVs), and VEX robotic design systems have been mainly used in the context of extracurricular activities, a wealth of new and rigorous research in education has come to the forefront illustrating the positive academic impact of educational robotics (Sullivan & Moriarty, 2009). Educational robotics has been shown to support applied mathematics and physical science learning as well as problem solving (Barak & Zadok, 2009; Hobbs, Perova, Rogers, & Verner, 2007; Martinez Ortiz, 2011). LEGO-robotics curricula have been shown to provide opportunities for the learning of mathematics, and the hands-on nature of robotics has led to a positive impact on student learning of complex mathematical ideas (Goldman, Eguchi, & Sklar, 2005; Mauch, 2001). Such research has also uncovered the motivational and affective impact of the LEGO-robotics engineering learning experience.

Guiding research question

Additional research is required to understand the full potential of educational robotics as an instructional support in the formal classroom setting and in the preparation of teachers. Our study proposes that even preservice teachers with very limited experience with engineering design and computer programming can quickly gain great confidence in their abilities to use and teach with educational robotics. This guiding-research focus motivated us to consider designing a brief but significant learning experience for preservice teachers that would introduce them to educational robotics via an integrated robotics themed module.

Integrated robotics themed module

An integrated robotics themed module was designed as part of a teacher-preparation course. The participants in this study were 25 preservice and in-service teachers in three different teacher preparation graduate courses—a mathematics method class, a science/mathematics class, and an educational technology class. To accommodate the three participant groups, two separate implementations were delivered. The three authors and faculty members (instructors) who teach these three courses teamed up to coteach the integrated robotics module at each implementation. The instructors not involved in teaching a particular module were responsible for collecting observational data of participants' actions and comments. Additionally, reflection essays were assigned and written by participants. These reflections served as qualitative data and were analyzed as described in the data analysis section below. Each implementation was exactly the same, consisting of a 2-hour session with hands-on experiences that involved a variety of topics, including (a) the engineering design process, (b) programming, (c) mathematical connections, and (d) a problem-based learning project. At the start of the lesson, all students possessed differing levels of experience with robotics; however, sufficient instruction on educational robotics was delivered to each group to enable them all to actively collaborate as part of a small group involved in learning using reverse engineering. Table 1 outlines the instructional structure of the integrated robotics module, which is described in detail next.

FIGURE 1

Preservice teachers engaged in a LEGO educational robotics STEM integrated lesson.

Lesson 1: Engineering design process

The first minilesson topic explored during the session was a 20-minute introduction to the engineering design process. The first 10 minutes were used to provide an overview of the engineering design process by discussing approaches to integrating these into the K–12 curriculum and background regarding engineering career trajectories in the real world.

That was followed by a 10-minute, hands-on challenge in which the students were placed in small groups and introduced to the robotics materials and then tasked with reverse engineering (taking apart a prebuilt LEGO robot and then rebuilding) the robot. Students were encouraged to use the engineering design process by focusing on the problem, identifying possible solutions while being resourceful and analyzing (on their own) ways to deconstruct and reconstruct the robot. During the final 5 minutes, students were given the blueprint plans of the robot to assist them in reconstruction.

Lesson 2: Programming

The second minilesson topic included a 20-minute exploration of computer programming. The introduction consisted of an interactive discussion of the prevalence of computer programming, and then the concept was broken down into a series of cause-and-effect relationships. That was followed by a 15-minute, hands-on experience in which students worked in groups of two or three to explore the LEGO Mindstorms software interface that they used to create two programs for their robot.

Lesson 3: Mathematical connections

The third minilesson topic involved facilitating connections between mathematics and the context of the robot. Prompted with a basic mathematical discussion of measurement, students worked in groups of two or three to hypothesize how they could measure the distance their robot would travel, factoring in how the distance traveled would be altered through the use of three different sets of wheels. Student groups were then given tape and a pen to create their own experiment to test their hypotheses. The third minilesson culminated with a review of mathematical concepts that arose from the students' experiments, including ratio, proportion, and circumference.

Lesson 4: Problem-based learning

The culminating miniproject involved a problem-based learning (PBL) exploration in which each small group chose a problem to investigate. Having been given a scaffolded introduction to the engineering design process, programming, and mathematical connections, students were asked to put the pieces together. Prompted with questions about classroom management and the K–12 student context, participants were continuously being asked to reflect on how the activities they were engaging in could translate to authentic content connections within their own classrooms.

TABLE 1

The integrated robotics module.

	Essential understandings	Minilecture	Hands-on experience
Lesson 1: Engineering design process	LEGO robotics technology can be used to teach the engineering design process to K–12 students.	Brief introduction to engineering design process (10 minutes)	*(Re)build the robot (10 minutes)* Introduction to LEGO robotics materials Deconstruct the robot Reconstruct the robot Reflect on the engineering design process
Lesson 2: Programming	Programming languages contextualize the process of cause and effect (variables, algorithms).	Brief introduction to programming (5 minutes)	*Program in LEGO Mindstorms software interface (15 minutes)* Introduction to LEGO Mindstorms software interface Change variables in existing program to experience the effects Create original program for robot to "start, go straight, stop"
Lesson 3: Mathematical connections	LEGO robotics components (bricks, gear, tires, etc.) possess a variety of mathematical qualities.	Brief prompt and instructions (5 minutes)	*Measuring distance (20 minutes)* Prompt: How do you measure the distance a robot travels? Generate five hypotheses Test hypotheses Share findings Review mathematical concepts
Lesson 4: Problem-based learning (PBL)	The engineering design process, programming, and LEGO robotics can be used to encourage K–12 students to solve meaningful problems in PBL units.	Brief prompt and open-ended instructions (5 minutes)	*Project: Put all of the pieces together (40 minutes)* Prompt: Identify a problem Solve problem Reflect and share findings

Participants and data analysis

There were 25 participants in this study. The majority of students in the study were female (female students = 31, male students = 4). The majority of students reported not having experience with educational robotics prior to this session (*none or minimal* = 20 students, *some* = 4 students, *significant* = 1 student).

Observational techniques were used to gather firsthand data on participant behaviors and additional data was collected through student reflective essays submitted by the participants after the instructional sessions. This information comprised the qualitative data set for this study and was analyzed using open coding. Coding or open coding (Charmaz, 2006) is a data analysis methodology that can be used to break down qualitative data into discrete parts, allowing the researcher to closely examine and compare them for similarities and differences (Strauss & Corbin, 1998, p. 102). This methodology was used to examine the written reflections of the 25 participating teachers.

Problem-solving approaches taken

On the basis of observational notes, many approaches were used to solve the problem of reassembling the robot; some students immediately started taking the parts off the control unit, confident they could put them back, and others either drew a picture or used their iPad to take a picture. One group took each piece off the robot and identified the purpose of the piece. Another participant said next time she would label each part. Some who struggled with the reverse engineering activity demonstrated lack of optimism and patience in their own selves (transdisciplinary skills) and relied on their teammates. One participant remarked, "I have to say that I have the utmost confidence in my colleagues and if I don't know how to solve a problem . . . someone will." The discovery approach takes more time than normal, particularly in the context of challenging curriculum. In a collaborative group setting, guidelines could be set to encourage supportive but relaxed exploration, with an artifact provided for each student to handle. In our lesson, although a time limit was set, with some assistance all robots were reassembled.

Integrated mathematics and critical thinking

After putting their robots together, students then estimated how far the wheel would go in one rotation and how many rotations the robot's wheel would take for the wheel to travel 100 cm and 200 cm. They checked their answer against the estimate and changed the wheel to a larger or smaller size wheel and estimated again how far it would travel in one rotation. Some figured out that $2\pi r$ would help them find the circumference, but after measuring the number of rotations, the estimates and actual measures did not match. Some conjectured that this was due to the drag of the surface. To prove their theory, they tried different surfaces and collaborated with other groups. Collaboration helped students to refine questions, think critically, collect and analyze data, draw conclusions, and share their findings with others. Teams with members who were curious and enthusiastic students did most of the work, similar to the findings of Karahoca, Karahoca, and Uzumboylu (2011). We also found that groups with better communication and enthusiastic students generated more ideas.

Transdisciplinary abilities and spatial reasoning

The reverse engineering activity and wheel activity challenged students to develop transdisciplinary, problem-solving, and visual-reasoning skills. The key skills that encompass the design thinker's personality profile, as proprosed by Brown (2008), are briefly defined as follows: The transdisciplinary abilities mentioned were *empathy* (the ability to imagine the world from multiple perspectives when design for function doesn't work); *optimism* (the ability to confidently approach the problem); *experimentalism* (the understanding that significant innovations don't come from incremental tweaks); *collaboration* (the ability to work within many disciplines and groups of people); and *integrative thinking* (the ability to engage in convergent and divergent thinking). A participant credited the activity's requirement for the use of visual thinking and spatial reasoning, and it was this skill that contributed to her ability to put back together what she had pulled apart. Cross-disciplinary skills were used including STEM and even art. Patricia, a student in the study, mentioned the use of measuring, predicting, comparing, experimenting, and using equation skills, such as finding that circumference and diameter are usable target areas for robotics mathematics problems. Some students suggested adding weight to the robots and predicted that a time variable would add a science component. The more the students talked, the more they could see how robots might even apply to an integrated storytelling scenario.

Findings

Teacher reflections

A coding scheme for analyzing participants' reflective essays was developed. The following six major themes were identified by analyzing their short reflective essays regarding their reactions to the integrated educational robotics (ER) module:

1. ER is fun and motivating.
2. ER is significant and important.
3. ER is a good way to integrate technology.
4. ER develops pedagogical skills in teachers.
5. ER develops cross-disciplinary skills in students.

6. General commentary of some reservations.

As can be seen in Figure 2, more than 80% of the 25 participants expressed feelings of delight and fun in working with the LEGO robotics components. Over 70% clearly described the effectiveness of the integrated STEM lesson and saw clear connections to cross-disciplinary skill development in students. Over 60% expressed support for the importance of educational robotics, programming, and integrated math and science learning experiences for students. Although most comments and observations was positive, about 12% of the participants expressed some feelings of being ill-prepared to teach in an integrated manner, or were hesitant about working and learning in an overly collaborative environment, or felt challenged by the technology or mathematics. Most participants valued the learning experience and agreed that it is never too early to introduce young students to engineering and robotics. The overall idea expressed was that the engineering thought processes should not be solely limited to secondary education nor to gifted and talented classes only. The boldness of their reflections regarding the future potential of such curricula speaks to the enthusiasm and the perceived scope of future developments in the field of robotic science. One participant said that as computers are central to the information age, robots could be central to the "robot age." Robotics is one of the "big industries of the future." Referring to educational technology, another student said, "With a more STEM-savvy populace, we need to discontinue the superficial treatment of technology in schools and begin deeper dives." With the application to other disciplines, LEGO robotics could become a viable component of K–12 education**.**

John, a student in our study, shared his view on LEGO robots in terms of the illusion of understanding based on the act of looking at something, or using it (technology), and therefore believing one understands it: "Knowledge must be combined with the tactile experience of real-world creation, experimentation, and behavior before we can claim to begin to understand something. The LEGO robots set us on a path to better understanding of the world because they give us the opportunity of tactile experience." He speaks powerfully about the need to apply, touch, play with, and problem solve.

Recommendations

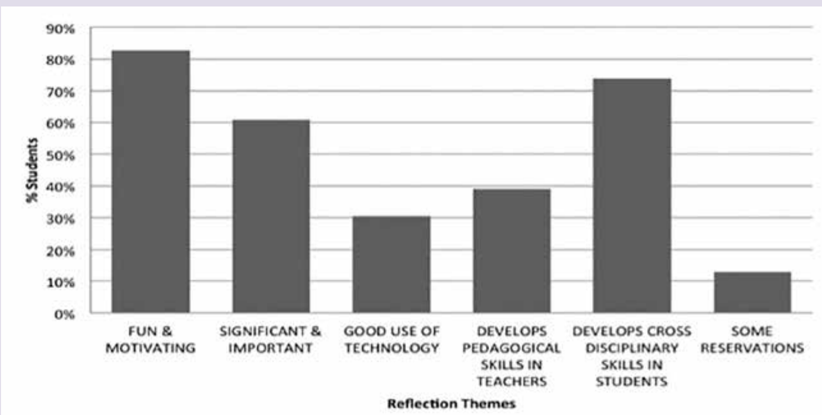
Preservice teachers must be challenged to experience what for many may be unfamiliar but exciting opportunities to play and learn with robots. Such experiences can be very effective when structured to integrate STEM content connections while using pedagogical approaches such as guided learning and scaffolded STEM instruction. Educational robotics, as we have presented, has the potential to offer teachers many opportunities for connecting math and science and integrating technology into their everyday K–12 classroom, instead of relegating this resource to only extracurricular time. The use of educational robotics allows for teachers to reinforce not only content, but also the eight science and engineering practices described by the NGSS.

State, national, and international researchers (Martinez Ortiz, 2014; Tai, Liu, Maltese, & Fan, 2006; Wood, 2004) have shown that very young children are capable of understanding and of being inspired by challenging hands-on learning experiences in STEM and that if they are not exposed to such experiences before high school, many start losing interest and self-esteem in STEM as early as 5th and 6th grade (Chen & Zimmerman, 2007; Seymour & Hewitt, 1997). Prioritizing and supporting STEM education is the key to a well-prepared future workforce and citizenry in Texas and across the country. These experiences need to begin with teachers and should be modeled as authentically as possible. The guided discovery approach with appropriate support lends itself to such learning and encourages the development of more transdisciplinary skills, problem solving, visual reasoning, and optimism. As seen in our study, participants should also have an opportunity to debrief and discuss their emotional responses to this learning. These discussions should address concerns regarding different learning styles, variances in levels of student experience and content knowledge, and issues of classroom management.

Preservice teachers can gain powerful insights by exploring with robots, programming, brainstorming, and

FIGURE 2

Top themes discussed in participant reflection essays.



problem solving. They can subsequently use this learning to guide their own students in early educational robotics learning experiences that integrate mathematics and science concepts. Carmen, a student in our study, clearly expressed her intentions to share her learning with her future students: "I truly have learned that if I can open my mind to these new ideas and technology, I can only imagine what I can bring to a classroom full of students." ■

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