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Examining the Role of LEGO Robots as Artifacts in STEM Classrooms (Fundamental)

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1. Introduction

Educational robotics has become a widely used technological and pedagogical tool in many K-12 classrooms across the United States [1]. The broad adoption and popularity of robotics in educational settings are attributed to its ability to engage students in enjoyable and meaningful experiential learning, as hands-on manipulation of robots contribute to knowledge construction regarding essential grade-appropriate STEM concepts [2]. In particular, the presence of programmable educational robots in STEM classrooms have significantly enhanced the nature and scope of science inquiry and engineering practices that can be conducted in K-12 classrooms, especially over the last decade.

The research examining the impact of educational robotics on student learning is extensive; ranging from its impact on student behavior, development, achievement scores, and engagement with content [1-3]. In general, the utility of robotics as a learning tool in STEM classrooms is supported by the theories of constructivism and constructionism [4, 5]. These theories form the basis of commonly utilized educational approaches involving robotics, such as project-based learning, collaborative learning, competition-based learning, and discovery learning [6]. Robots are considered to increase engagement and aid knowledge construction by virtue of their physical embodiment, as compared to screen-based learning interfaces [7]. Robots have also been shown to increase student interest in engineering and improve their conceptual understanding of math and science by engaging them in interactive learning experiences [1].

Broadly the role of educational robots in classrooms has been classified into three categories: (*i*) tutor, (*ii*) peer, or (*iii*) tool [8]. Yet, the role of educational robots as technological and educational artifacts in K-12 STEM classrooms has not been examined in depth by researchers. One reason might be attributed to some researchers considering student learning to be curriculum dependent [9]. In this school of thinking [9], the use of educational robots is not guaranteed to improve student learning, rather the role of educational robotics in K-12 settings is to foster the development of critical 21st century skills, such as, creative thinking, problem solving, collaboration, and communication. These researchers consequently view the current challenges in the field of educational robotics as those pertaining to promoting and supporting widespread implementation, as opposed to the study of their impact on learners. Some innovative strategies recommended for effective classroom integration and implementation of educational robots include: (*i*) developing projects that focus on themes and not just challenges; (*ii*) combining art and engineering; (*iii*) encouraging storytelling; and (*iv*) organizing exhibitions rather than competitions [10].

The aforementioned approach, which considers the role played by educational robots to be in the development of broad skills, *viz.*, cognitive and language skills such as research skills, creative thinking, problem solving, and collaboration, appears to consider that development of life skills would occur separately from conceptual understanding of educational content. However, as other researchers have shown, learning in the presence of technological artifacts is non-trivial in its complexity, and must be analyzed while taking into account the working environment [11]. Thus, we posit that the goal of developing an in depth understanding of the role that educational robots play as artifacts in STEM classrooms cannot be divorced from the effort in achieving their widespread adoption in such venues.

In this work, we attempt to examine the role played by educational robots (LEGO EV3) as technological artifacts in K-12 classrooms in three science and math lessons. We begin by reviewing the various approaches used for studying technological artifacts in K-20 education. We then discuss the theoretical framework, i.e., Vygotsky's zone of proximal development, which is used to guide this work. Next, we present the pedagogical contexts in which the educational robots were deployed in the three example science and math lessons examined in this work. We then examine the qualitative data to answer two key questions: (*i*) what role did the robots play as educational artifacts in scaffolding student learning? and (*ii*) what challenges were observed that affected student learning? As more K-12 schools continue to invest in robots as educational tools, it is imperative to develop a more nuanced understanding of the contribution of educational robots through the lens of their contributions towards student learning.

2. Literature Review

In the last two decades, increasing attention has been devoted to understanding the role of the artifacts in the learning process. One such area of research interest employs a situative perspective [12, 13] to study implicit messages that students receive regarding the content of their education based on the physical environment in which learning takes place. The situative learning perspective emphasizes the role of 'participation in meaningful activities' on learning, e.g., see [13] for its relevance to engineering education. In particular, as the practice of engineering is heavily dependent on the use of physical materials, interactions with them become imbued with 'social and material' contexts such as symbols, representations, and their manipulation [13].

In fact, researchers have argued that a focus on utilizing technology artifacts only as a means to develop conceptual skills in students may lead to 'black boxing' of said artifacts [14]. Black boxing refers to utilizing the technology artifact as a 'passive or end tool' [9], a process that often significantly limits the scope of their application. Thus, researchers suggest that in science classrooms and laboratories, both educators and learners ought to be encouraged to consider how the presence of artifacts such as precision instruments affect scientific practice [14].

To begin with, different researchers studying educational artifacts have utilized varied approaches for examining and reporting on them. The socio-cultural theory [15] has been used to organize classroom artifacts to be studied into categories, such as concrete carriers (furniture), concrete conveyors (display devices e.g., computers, projectors, screens, document cameras, blackboards, handouts), inscriptions (graphs, charts, equations, diagrams), texts, virtual artifacts (online, gestures), and ambient artifacts (noise, glare) [12]. The socio-cultural theory framework has additionally been used [12] for examining relationships between the physical placements of classroom artifacts and the implicit meanings generated by students and educators, e.g., how students and instructors perceive the nature of instruction in a classroom to be, as implied by the placement of the furniture, or the presence of technology-assisted display devices.

Other researchers adopted an instrumental approach for examining and reporting on technological artifacts [16] used in K-12 math classrooms [11] and the associated learning process. An instrument is defined as both the artifact and the accompanying mental schema that the students use to perform an educational task. For example, the instrument for solving the equation of a parabola will be composed of a graphing calculator and the knowledge or skill of how to manipulate the artifact. This approach organizes artifacts by the 'problem-solving strategy' adopted in relation to them. Additionally, researchers have also explored the roles played by educational artifacts due to their materiality, and have shown that they contribute to scaffolding student performance by: (*i*) building 'common knowledge'; (*ii*) supporting critical thinking; (*iii*) making 'new things visible, or familiar things visible in new ways'; (*iv*) problematizing; and (*v*) serving as an adjunct to talk [17]. These include examples of 'touching to understand' or 'haptic perception' such as to distinguish between solids and liquids. The materiality of student created artifacts has also been shown to 'anchor and/or augment' students' in their interactions with peers.

The examination of robots as educational artifacts is necessarily more complex than the aforementioned classroom artifacts by virtue of their embodiment (which can be expressed on a 'hypothetical progressive scale' as described in [8]) and being technology-based artifacts. Researchers have previously argued that experiences with technology-based artifacts must be treated as 'a distinct realm of human experience' that partly derive from the human-technology interface itself [18]. Any technology-based artifact, such as a graphing calculator being used to solve the equation for a parabola, requires the user to understand and communicate with it using the schema that it uses for organizing, representing, and manipulating symbols and knowledge. Techniques used for problem solving often differ subtly between manual methods and technology-supported methods, making the process of knowledge translation across platforms non-trivial. Thus, nuances such as increased complexity due to additional requirements for symbolic representations and manipulation of problems and implementing them on a new technology device [11] must be taken into account while incorporating technology-based artifacts.

Informed by the aforementioned literature review and with the ever-increasing use of educational robotics to support learning in K-12 classrooms and beyond, it is essential that greater attention be directed towards the different features of these complex and non-trivial technological artifacts. Prior studies on technology-enabled K-12 math education (e.g., with the assistance of graphing calculators, computational geometry software, etc.) have dominated the field of artifact research in education, *viz.*, examining the impacts of artifacts, their affordances, and the teacher-student interactions associated with them [11]. Use of some devices, such as calculators, separate the need to perform tedious calculations from the conceptual understanding. In contrast, the use of robot-type artifacts support the implicit understanding that the development of technical skills promotes conceptual understanding. Recent years have witnessed the initiation of work in examining the role of robots as educational and technological artifacts in K-12 classrooms. For example, researchers have investigated what kind of robotics programming tasks can be used to scaffold the development of computational thinking in students [19]. In a similar vein, an analysis of the effects of technological artifacts (*viz.*, robot) on student learning in the context of different pedagogical resources and classroom settings is necessary to develop a holistic view of their potential roles.

3. Theoretical Framework

In this study, we used the concept of zone of proximal development (ZPD) introduced by Vygotsky as our theoretical lens. The ZPD is defined as 'the difference between the level of solved tasks that can be performed with adult guidance and help and the level of independently solved tasks' [20]. Alternatively, it may be defined as 'the zone of activity in which a person can produce with assistance what they cannot produce alone (or with difficulty)' [21]. The ZPD connects the level to which a student is able to develop her capabilities to the instruction she receives. It theorizes that well organized instruction, embedded in the curriculum design and/or enacted by the educator, supports a series of inner developmental processes in the learner that would not be possible in its absence. One way to achieve this can be through scaffolding. Effective scaffolding for supporting instruction might focus primarily on (*i*) engaging student interest in the task, (*ii*) simplifying the task by reducing its degrees of freedom, (*iii*) maintaining student motivation and focus towards the task at hand, (*iv*) supporting students in identifying discrepancies by marking critical features, (*v*) managing student frustrations, and (*vi*) modeling solutions to the task [22]. Researchers have also suggested that scaffolding need not be provided by tutors or peers alone, and might even be provided by tools [23]. Tools or artifacts can support learners by automating certain actions or reducing the amount of work that students might need to do, e.g., using calculators to perform complex arithmetic operations. Artifacts can also help students to visualize or represent information more conveniently.

In addition to its use in traditional classroom settings, the concept of scaffolding has also been used to examine learner progress by using software tools and other computer and technology-based artifacts commonly used in educational environments. In particular, the concept of ZPD has been utilized to design screen-based educational artifacts that can provide effective scaffolding [24]. In this work, we will expand the scope of the concepts of ZPD and scaffolding to examine the contributions of educational robots in providing the students assistance that might enable them to achieve more than they would otherwise.

4. Method

Context and Participants: For this research we observed a three-hour exposition day hosted at the NYU Tandon School of Engineering. In attendance were 30 middle-school students, four high-school students, six teachers, and one chaperone, in addition to graduate fellows, researchers, and faculty affiliated with a teacher professional development (PD) project. The six teachers in attendance had previously participated in a summer PD program [25] and created four robotics-enhanced STEM lessons with the support of project personnel. In the following school year, they implemented the lessons in their classrooms, with support from the project team. Moreover, as a follow-up to the summer PD project, each teacher collaborated with their students to develop, modify, and implement a new STEM lesson in their classroom. At the end of the academic year, the teachers and up to six students from each school, presented the new lessons to fellow teachers and students. The details for the six teachers are provided in Table 1.

Table 1: Details of participating teachers

Teacher Alias	Subject	Gender
Teacher 1	Math	F
Teacher 2	Math	M
Teacher 3	Science	F
Teacher 4	Math	F
Teacher 5	Science	F
Teacher 6	Science	F

The authors’ institution was chosen as the venue for hosting the exposition, as it is an institute of higher education. The program personnel wanted to utilize this occasion to create an opportunity for students from inner-city public middle schools to visit an engineering institution and gain an experience in presenting their work to peers and professionals for feedback. This event allowed teachers and students from different schools to interact with one another and observe classroom practices and techniques used in other schools in the city. Students were able to see a wide range of applications of robotics in math and science and get inspired by the creativity and initiative displayed by their peers. They were also exposed to a range of free and tuition-based summer programs that are offered through the authors’ institution for K-12 students. It was a productive session resulting in a great learning experience for all participants. The exposition was scheduled for a period of three hours and included brief addresses by the program personnel. These were aimed at explicitly stating the goals of the exposition and sharing the effort put in by the teachers over the previous summer in the PD program, to allow participants to appreciate the nature and purpose of the event. Each teacher was allocated 15 minutes for presenting their lesson, followed by demonstration of the artifacts created. The details of the lessons presented are summarized in Table 2. Corresponding to the three case studies discussed in section 5, details for the lessons of Teachers 1, 2, and 3 are also provided below.

Table 2: Details of lessons presented by the teachers

Teacher	Subject	Lesson	Class Periods	Robotic Activity
Teacher 1	Math	Ping pong lessons and parabolas	3	Ping pong launcher
Teacher 2	Math	A system of linear equations	3	Draw two straight lines using EV3 robots and find their point of intersection
Teacher 3	Science	Measuring distance with sound waves	1	Display distance measured by ultrasonic sensor on port view of EV3
Teacher 4	Math	Forces and interactions	2	Observe position and direction of motion of wooden block pushed by EV3 robot
Teacher 5	Science	Echolocation	1	Record distance at which an EV3 robot detects obstacles using ultrasonic sensor and stops
Teacher 6	Science	Laws of motion through tug of war	2	Modify gears, wheels, and mass to win a tug of war game with EV3 robots

Teacher 1 (8th Grade Math): Ping pong lessons and parabolas

Teacher 1 based the math lesson titled ‘Ping pong lessons and parabolas’ on her love of the sport. This pre-calculus mathematics activity was designed to introduce students to a real-world application of mathematics and can also serve a science or physics class activity. She introduced the concept of parabolas to students as the mathematical model for the path of a ping pong ball as a function of time, as shown in Figure 1. Students were tasked with building a LEGO EV3 ping pong launcher according to a template she provided to them. Expanding on the understanding gained through this process, students were challenged to modify the ping pong launcher to maximize the height of the ball launched.

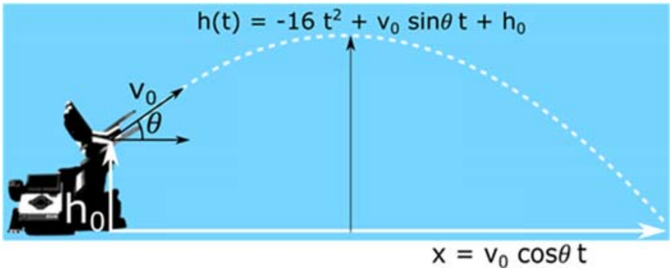

Figure 1: Schematic of activity accompanying the lesson 'Ping pong lessons and parabolas'. Students observe the relationship between the maximum height h that a ping pong ball can achieve and variables such as initial launch velocity and initial launch height.

Teacher 2 (8th Grade Math): A system of linear equations

Teacher 2 presented a multi-part lesson on the topic of 'A system of linear equations.' In this lesson, first LEGO EV3 robots were used to explain the concepts of proportionality and rate of change or slope to students, as depicted schematically in Figure 2. Once these concepts fell within the students' ZPD, they were encouraged to expand their understanding of equation of a line to systems of linear equations. Students explored three different methods for solving a system of two linear equations, namely, elimination, substitution, and graphing. As a final project, the instructor encouraged students to draw from their personal experiences to identify a real-world problem that might be solved by using a system of linear equations. The storylines presented by the students were suitably simple and expressed as a system of two linear equations. The students then solved the resultant system of equations graphically using the robot. The robots were programmed to move along the two straight lines representing each constraint, and the point of intersection was found visually. Students then verified the graphical solution using the elimination and substitution methods.

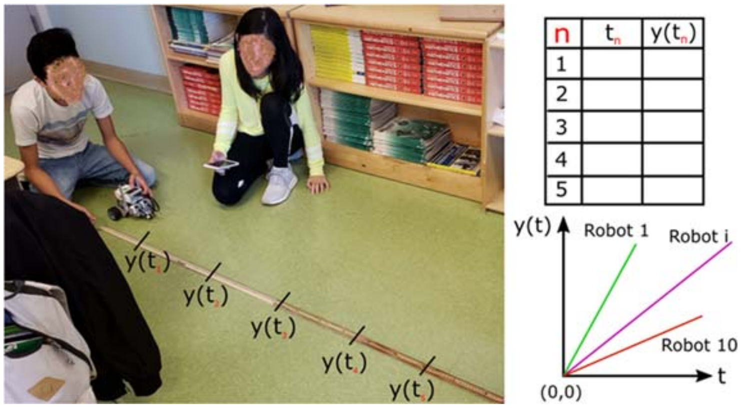

Figure 2: Schematic of first activity accompanying the lesson 'A system of linear equations'. At ten different stations students use different LEGO robots operating at different speeds to explore the concepts of proportionality and slope or rate of change, and learn to formulate the direct variation equation, i.e., y = Kx.

Teacher 3 (10^{th} – 12^{th} Grade Bioengineering): Measuring distance with sound waves

Teacher 3 taught a project-based bioengineering class to students ranging from 10th -12th grades. Through the lesson titled ‘Measuring distance with sound waves,’ students explored how different properties of waves are used in various technologies and instruments (e.g. ultrasound machines, sonars). Students were provided with LEGO EV3 bricks with ultrasonic sensors connected. Students collected distance data from the sensor using the EV3 brick’s port view and used the known speed of sound in air to calculate the time it took for the sound to travel the measured distance, as shown in Figure 3. They verified their calculations by using rulers and stop watches. Then they observed the time taken and used it to calculate the distance traveled. They also calculated the frequency of the sound wave.

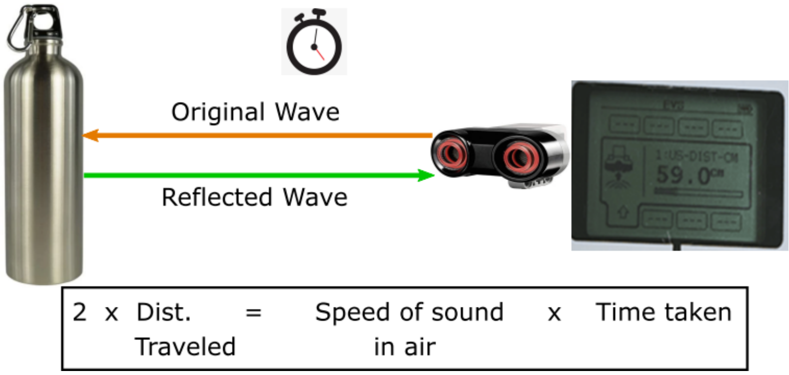

Figure 3: Schematic of an activity accompanying the lesson ‘Measuring distance with sound waves’. Students use LEGO robot to measure distance to an object placed in front of it and calculate the time taken by the soundwaves emitted by the sensor to reach the object.

Data Collection and Analysis: For the purposes of analysis of the role played by the LEGO EV3 robots as educational artifacts, video data was collected of the presentations made by the participants on the exposition day. Consent was obtained from all subjects. Two wide-angle cameras were placed in the event space, one facing the speaker, and the other was placed to capture the front of the room where the artifacts would be demonstrated. The video data from the exposition day was then transcribed verbatim by the lead author. Next, the transcript was enriched with additional audio-visual material and details of physical demonstration materials used in presentations. The transcript was coded for themes relating to ZPD and scaffolding, as presented in the theoretical framework section, using a deductive thematic analysis approach [26]. For triangulation, the transcript of the video data was compared against the lead author’s sparse notes, taken during the exposition, and with the content of the presentations, lesson plans, and student worksheets provided by the participant teachers.

5. Results

Case study 1: Building a ping pong ball launcher robot

As described in the previous section, Teacher 1 provided the students of her eighth-grade math class with the example of the trajectory of a ping pong ball, launched from an initial height h_0, as a parabola. The students were tasked with building a basic ping pong launcher robot. The pedagogical approach utilized can be construed as a combination of discovery learning and competition-based learning approaches [6]. Prior literature [6] reports that it is expensive to organize robotics competitions for students and to engage the general student body in such competitions. Thus, while competition-based learning remains a very effective pedagogical technique, it is traditionally utilized for informal and afterschool programs only [6]. The LEGO EV3 robotics kit provides an assortment of mechanical parts that could have been used in varied combinations to solve the given problem. To reduce the degrees of freedom in the problem, the teacher provided her students with a set of instructions, including a specific design template for building the robots. All but one team of students in the class built the ping pong launcher robot by adapting ideas from the design template. The 'rouge' team built a slingshot robot, and a picture of both the ping pong launcher robot and the slingshot robot are provided in Figure 4. Their decision to build a different robot led to an extended conversation in the class, involving the teacher and all the students. Many students felt that the rouge group should not be allowed to build a different kind of robot, as it would be akin to 'cheating', by potentially giving them an unfair advantage. However, after listening to all concerns, the teacher agreed to allow the students to build their own robot and she rationalized as below.

> *Teacher 1:* What's wonderful about working with robots is that you have the degree of freedom to go ahead and research your own model and to then improve on whatever you have. So, there's a lot of creativity that can come with that. So, lot of student choice, which I think is really important in school setting.

Through the example of the students engaging in the development of the slingshot robot, we are able to observe one of the key advantages of the use of robots in classrooms. It provides interested and enthusiastic students an opportunity to generate more ideas, engage in spatial reasoning, and engage in engineering design. Moreover, from this example, we can see that for some students, the process of robot construction is a source of enjoyment and motivation. However, for some other students in the class it was a stressful task and they wished to focus on the practical task of creating the required artifacts based on the template. The slingshot robot involved significantly greater mechanical complexity as compared to the ping pong launcher robot, involving the use of gears and axles. The process of creating this complex robotic artifact gave the students belonging to this team a great deal of self-confidence, and they also displayed a good grasp of technical vocabulary and a good understanding of the mechanics of the system while presenting their work as evidenced below.

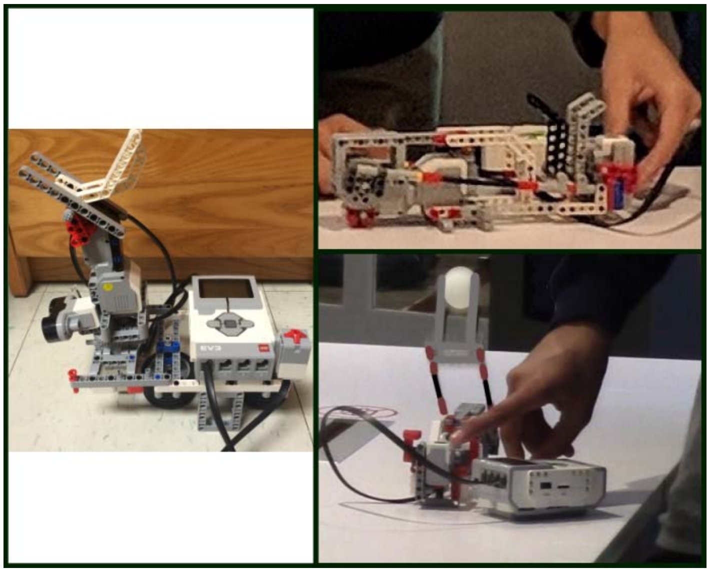

Figure 4: Pictures showing the structures of the ping pong launcher robot (left panel) and the slingshot robot (right panel) constructed by the student teams in classroom 1.

> *Student 1:* In order for this slingshot [robot] to actually work, we used a 1:5 gear ratio for more torque rather than speed. We needed it to go higher and farther and to actually have power […]. Normally it's not very useful because there's not much speed to it […] so we decided to add these, like, little pieces to act like barriers […]. So basically like the slingshot is, like, going against the force of those parts so it creates more power for the slingshot and it goes much farther and higher.

It can be seen here that while the students have some insight into the process, during Q&A they quickly grasped the concepts that they were being quizzed on by a mechanical engineering faculty and exploited the underlying guidance to appropriately demonstrate the importance of the feature to their peers, and even their teacher, as can be seen from the exchange below.

> *Faculty:* How did you come up with the idea of using the blocks? [...] And using them to add momentum?
>
> *Student 2:* Normally the robot wouldn't do much. It's very impractical. So, we added these little block parts so that - what they do is they block the axle from moving over. When we add them on and put them in the right place, what it does it - it builds up force, and then it moves, so the robot can launch very far.
>
> *Faculty:* Can you move it once without the piece connected? How far does it go? [Students demo that the arm gently drops the ball] [...] And then again with the piece connected? [Students demo that the arm shoots the ball much farther].

This example also shows how the materiality of the robotic artifact developed by the students anchors their interactions, not only with their peers, but also with other faculty and subject matter experts. We now compare the conceptual understanding of the physics behind parabolic trajectories developed by students with a different group that built a ping pong launcher robot using the teacher-provided template. One of the students spoke as follows.

> *Student 3:* [...] like, let's say, you think that this would work because, it [the launcher arm] would go that way [at an obtuse angle to the vertical] and it would give it a thing [greater power/ height], but that is very [...] it's useless, it doesn't do anything. And then, if you have it right on top, it has better effect. But we discovered, but what we saw, we felt like at 90 degrees, or like just under 90 was the best. So, it was trial and error. This entire robot was trial and error. And eventually we found something that works. Well, it's not very stable.

This last statement points to a sense of frustration that the students felt in trying to work with the robot. Their statements indicate that the robot did not perform according to their expectations. It might point to a lack of deeper understanding of the underlying mathematical concepts, or alternatively the reasons for the behavior of the robot. As a result, the students appeared to be using the robot as a 'black box' device, even though they built it themselves by following step-by-step assembly instructions from a template.

While discovery learning provides students with a broad mandate and gives them the freedom to explore, in fact, an argument can be made for a need for further simplification of the task for the team in question. For the establishment of the ZPD, the proposed setup must produce in the learner a reasonable sense of being able to 'recognize the solution' [22], which appears to be lacking. The students were also daunted by the lack of built-in supports in the robot platform to identify, indicate, or prevent design errors. That is, while the LEGO robotic kits allow a great deal of mechanical freedom and flexibility for design exploration, it does not offer mechanisms for structuring student work, which are often built into special purpose educational software. To successfully modify the ping pong launcher robot, the students needed to understand the underlying mechanics of the system. While they were provided with an initial template for building the ping pong launcher robot, more adaptive and individualized scaffolding strategies were needed for the group of students being discussed in this example. Such support with regard to robot construction and programming can be provided by means of online videos or tutorials in a just-in-time manner.

Case study 2: Storylines for linear systems

As mentioned in the previous section, Teacher 2 used student-generated story lines to drive the final project following a series of lessons on a system of linear equations with his eighth-grade class. Storylines presented by the students included: comparing the amount of debt accrued by students attending two different Ivy League colleges, comparing the time taken by high speed bullet trains to travel the same distance, comparing the number of cellphones manufactured by two leading consumer brands in a given time, comparing the time taken by two electoral candidates to poll the same number of votes, and comparing the cost of stay at two different hotels during a vacation, among others. The teacher gave his rationale for this approach as follows.

> *Teacher 2:* So, I always feel that when you involve your students with the real-life situations, they take the sense of ownership, and they try to get involved in the best level possible.

This also provides the students an opportunity to work on other skills besides mathematics, and Teacher 2 collaborates with colleagues in subjects such as science and social studies to support student growth, as seen below.

> *Teacher 2:* In eighth-grade we are doing work involving real-life situations; you are asking them to precisely come up with the story lines including ELA, doing research about the situations, so you are doing lots of analysis of the data.

A collaborative learning approach [6] is utilized here, and the role of educational robots in this scenario is to motivate students, and to foster the development of essential 21st century skills. The storylines presented by the students included multiple elements that generated much interest and discussion among the audience, sometimes due to the use of pop culture references in the names or situations described, as evidenced below.

> *Teacher 2:* This was a graph and model used by student X for negative slope. Her storyline is submarines. Her dream is to be a Navy SEAL.

The interest generated by the use of story lines certainly positively affected student interest in the topic of systems of linear equations. LEGO robots were used to sketch the lines given by each of the two equations of the system, and then the point of intersection provided the graphical solution for the system of equations, as shown in Figure 5. Advanced students programmed the robots themselves.

> *Teacher 2:* So, what did you do to come up with these lines [referring to lines marked on the graph]? Can you explain to the group?
>
> *Student 1:* I wrote the line and slope identities to the robot, and placed it on the y-intercept, and I ran it to see where the lines would meet.
>
> *Teacher 2:* Did you use the same program for both lines?

> *Student 1:* No, I used two different programs for two different equations.

In this example we observe an application of educational robots in the 'black-and-white box' paradigm [9], i.e., the students are provided with pre-constructed mobile robots, and they utilize them to program the robots to accomplish the task of moving along well defined straight line paths.

This activity was not only a fun and engaging addition for advanced students, who would benefit by observing the geometric interpretation of the concept of linear systems of equations, but it also allowed students to access their prior knowledge relating to direct variations, and expand on it (ZPD), as can be seen from the brief dialogue below.

> *Student 2:* This was our first design. We did this one first in class. But then we tried to make a different one [system of equations], so we tripled the numbers. We put that on that [points to a different graph] graph, but since they were all tripled, the lines would still intersect on the fifth day [original point of intersection].

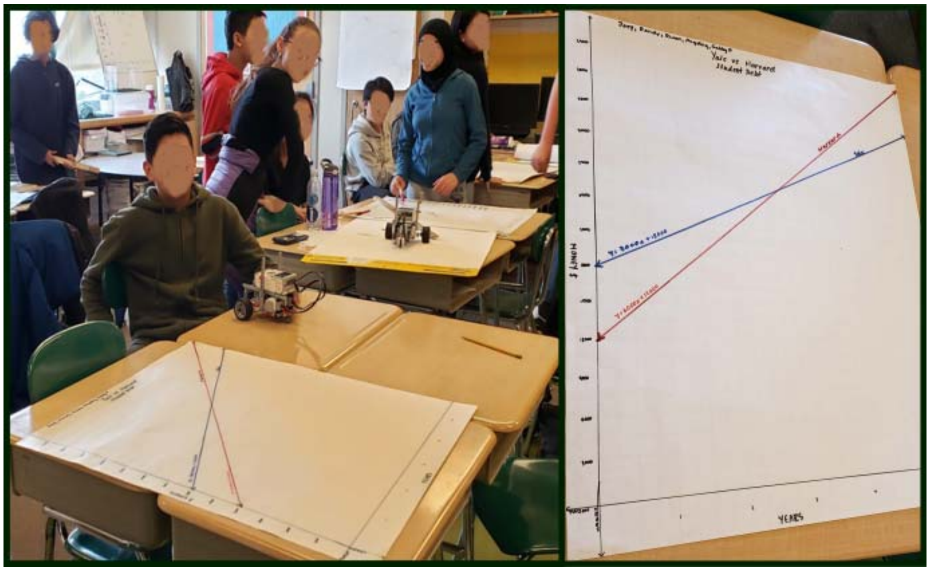

Figure 5: Pictures from classroom 2 showing students solving a system of linear equations graphically by using LEGO robots. Students write two programs, one for each of the two linear equations, and provide it information regarding the slope and intercept of each line and then run it to find the point of intersection.

Case 3: Using EV3 brick's port view

Teacher 3 developed a lesson that used the ultrasonic sensor of the LEGO EV3 robot kit for simulating the process of real-world sensing applications. The use of LEGO robots in this classroom differed from all the other classrooms in the way that it did not require any construction or programming. Teacher 3 used the inbuilt functions of the EV3 brick to design the activity and the related worksheet. There was no set up time required for the teacher or the students.

The activity assigned has been described in the previous section. Students recorded distance data displayed on the EV3 brick's port view and using the definition of speed, they calculated the time it took to travel the distance measured. Similarly, they calculated distance traveled for the measured time that an ultrasound signal took to hit an obstacle and be detected by the sensor. After the students completed the project worksheet assigned to them, they were asked to complete reflections about their experience.

The use of EV3 bricks allowed the students of different grade levels to perform this activity in regular classrooms, without needing to access specialized laboratories equipped with electronic components such as ultrasonic sensors. However, the use of EV3 bricks for sensing faced issues with accuracy and reliability depending on its placement with respect to the object being studied and required repeated interventions by the instructor during the activity, as can be seen in Figure 6. We argue that such breakdowns while using an educational robot increase student frustration and might affect the value of the artifact in promoting student learning.

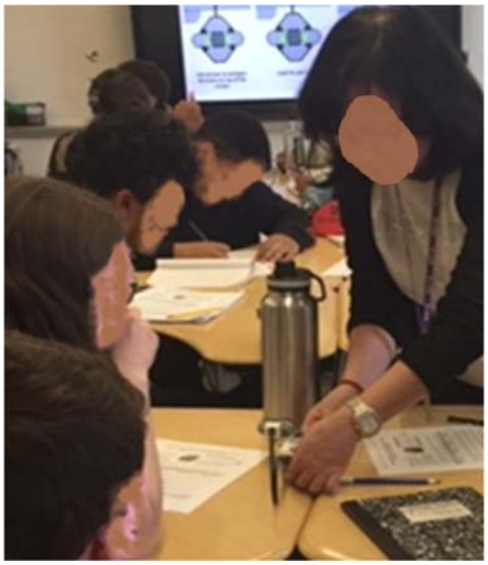

Figure 6: Picture from classroom 3 showing Teacher 3 intervening as students perform activity with robot and ultrasonic sensor to provide support to a group of students.

One student felt that the worksheet and the activity done in the class was too simple and that they could have gone into greater depth regarding the technological details of some of the real-world applications. Thus, there was a trade-off between the reduced set-up time for the activity by using the EV3 brick as an ultrasonic sensor and the scope of the activity itself. A mobile robot equipped with the ultrasonic sensors could have been used to simulate its real-world applications in a more authentic and meaningful manner. Another student reflected as below.

> *Student 1:* I was an AP Physics student. So, this wasn't anything new to me, I guess. But just the way that it [the worksheet] was formatted - I understood the equation - but I know that some of the students had a lot of trouble, since it was a bioengineering class. A lot of kids have a lot of interest in biology, so this wasn't probably the easiest thing for them to understand.

Similarly, it can be seen that while the EV3 brick performed well up to its mandate, it was unable to provide sufficient scaffolding for students for whom the concepts were completely new. While at the end, all students were able to complete the activity successfully, it is still important to consider ways in which the role of the robot can be strengthened.

6. Discussion and Conclusions

The aim of this paper was to analyze the use of robots as educational artifacts in K-12 classrooms by means of several case studies. To accomplish this task, we examined three robotics-enhanced science and math lessons presented by a group of teachers and students during an annual exposition day. A qualitative analysis was carried out in order to identify: (*i*) the roles played by the educational robots in scaffolding student learning and (*ii*) the challenges to scaffolding student learning while using robots as educational artifacts. Although the three case studies presented in this paper use LEGO EV3 robots, the results of this work can be generalized to different types of robotic platforms.

In the first example, we observed that the robots served as tools for fostering scientific enquiry by allowing students to exercise their creativity in design, build, and program activities. Moreover, the use of robots allowed students to engage in engineering design and exercise their spatial reasoning skills. This case shows that in the appropriate context and with proper scaffolding, implementation of a 'white box' approach, sometimes seen as too time consuming for traditional school environments, produces better learning outcomes. Conversely, some students in the classroom still faced challenges in building their robot while using the template provided to them. LEGO robot design kits are inherently 'white boxes', and hence, do not have the capability to identify or prevent students from committing design errors. This can contribute to increased student frustration, which can only be mitigated by careful management of students by the instructor. It calls for an adaptive scaffolding approach that is centered around individual student needs. Possible solutions for managing student frustration or disengagement may include redirecting them from trial-and-error approaches towards resources such as online tutorials, forums, or discussion groups where they can observe different solutions being modeled for the tasks provided to them. Such digital resources might even be linked with educational robotic kits.

The robotic artifacts created by the students also help them present their work in front of a wide body of their peers in a confident and authoritative manner. Finally, this example shows that it is possible to implement a competition-based learning approach within formal educational settings successfully and provides guidelines for mitigating major pitfalls.

The second case study provides an example of project-based approach towards integrating educational robots in K-12 classrooms, where the robot was used to foster the development of essential soft skills in the students. The robot provided cognitive mediation for students to understand mathematical concepts such as proportionality and rate of change through a geometry activity. During the activity, the robot's motion helped students link the concepts of two-dimensional space, position, and directionality with their mathematical representations, and expanded the range of reasoning they could perform. As students became competent in working with the aforementioned mathematical concepts, the instructor introduced systems of linear equations and the three different methods to solve them. The learning goals were further realized through the development of storylines by students and translating them in appropriate systems of linear equations. The robotic activities additionally facilitated the development of language, collaboration, presentation, and research skills in the students. The use of the technological artifact allowed them to practice additional skills of translating their manual representation to a symbolic representation that is device compatible. The use of LEGO robots for solving the system of linear equations graphically allowed some students the opportunity to visually access and build upon their prior knowledge with direct variations to understand the behavior of linear systems.

In the third case study, an example of a 'black box' application is presented. Students utilized the sensors attached to the robot processor to measure and observe its environment. As expected, it had the least set-up time, and it facilitated performance of procedural tasks. Further, problems with sensor usability, accuracy, and reliability arose when attempting to use the sensors provided with the LEGO robotic kits for data collection. This can be expected considering the fact that the LEGO robotic kits are not high precision scientific instruments, and the sensors provided with them are meant to function in a general manner to enhance their usability. Additionally, as evidenced from student reflections, the robot was not able to provide sufficient scaffolding to novice students during the activity. Further, the activity itself was seen as limited in its scope by students, as the robot was only used as a sensor.

Summarizing the above discussion, we describe the primary roles that LEGO robots can play in scaffolding student learning as: (*i*) fostering engineering design and creativity among students; (*ii*) enabling learners to visualize information in alternative ways; and (*iii*) empowering students to communicate with others regarding STEM concepts. Some key challenges that exist in using LEGO robots as technological artifacts to scaffold student learning include: (*i*) lack of built-in mechanisms to guide individual students and (*ii*) inability to independently support problematizing by students. Further research is required to explore the complete dynamics of scaffolding that occur during the implementation of robotics-enhanced lessons in K-12 STEM classrooms.

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