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Analyzing Successful Teaching Practices in Middle School Science and Math Classrooms when using Robotics (Fundamental)

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1. Introduction

Integration of robotics technology as a pedagogical tool in science, technology, engineering, and math (STEM) education is recognized to have the potential to enhance student engagement [1,2] and learning outcomes [1,3]. A curriculum infused with robotics-based learning activities offers numerous opportunities to enrich STEM education for students (e.g., through problem-solving [1,2,4], service learning [2], social interaction [5], teamwork [3,4], etc.) and it enables teachers to integrate engineering [1—5], computing [1—5], inquiry [1], and projects [4,5] into science and math education. Prior studies have acknowledged the significant role of robots in supporting myriad educational activities and outcomes in classrooms, e.g., engagement in active learning [3], embedding kinesthetic experiences in learning [6], imparting intrinsic and extrinsic motivations to learners [6], and producing student satisfaction [7], all of which illustrate the potential of a robotics-focused educational framework.

The use of teaching practices that effectively and successfully integrate robotics-based learning in middle schools STEM curricula can serve an "attitudinally influential" [8] role due to their potential for nurturing and sustaining the interest of middle school students in science and math. Nonetheless, current research has not paid sufficient attention to formally examine and identify such robotics-based teaching practices. Prior research [9] suggests that effective classroom teaching practices encourage interaction between educators and learners, embed opportunities for active participation of learners, impart motivation to them, and offer timely feedback. Moreover, educators ought to be intimately familiar with and have a deep understanding of common misconceptions of content knowledge held by students and should proactively address them [10].

This paper is concerned with identifying and analyzing teaching practices that can support successful integration of robotics-based lessons and activities in middle school science and math classrooms. To do so, a survey was administered to 23 teachers who have implemented robotics-based STEM lessons in their classrooms. Moreover, student performance was investigated with pre-and post-tests in one science lesson and one math lesson, both of which were implemented in classrooms by using a robotics activity and a non-robotics activity. Combining the analysis of survey responses from 17 teachers, observations of robotics and non-robotics activities in four classrooms, and learning outcomes of 88 students helped identify several successful teaching practices for integrating robotics-based science and math lessons in classroom teaching and learning.

This paper is organized as follows. Section 2 describes the literature review and Section 3 presents the theoretical framework used in this study. Section 4 describes our professional development (PD) program in brief while Section 5 presents the science and math lesson that were observed and assessed. Section 6 describes the research conducted for this study and Section 7 highlights the results of teacher surveys, classroom observations, and pre-/post-tests of students. Section 8 presents the discussion of the results and Section 9 provides conclusion and discusses future work.

2. Literature Review

Adopting the use of robotics in middle school education is important because, as students begin to consider future education and careers opportunities, engagement in positive STEM learning experiences that impart a sense of success and competence [11] can arrest the early decline of their STEM interest [8] and prevent them from souring on these fields prematurely. The interdisciplinary nature of robots, involving mechanisms, motors, sensors, controllers, and programs, make robotics a useful pedagogical and technological tool [12] that inspires students to start thinking of engineering as a viable career choice [13]. Robotics has been deemed useful in enhancing achievements of middle school students and improve their motivation for learning [14]. Furthermore, applications of robotics in K-12 STEM education provide opportunities to enact varied learning frameworks, such as cognitive apprenticeship, situated cognition, and collaborative and inquiry-based learning [15,16], which can promote student engagement and enhance their learning. Providing PD opportunities for STEM educators to adopt best teaching practices in the classroom is essential [17] for their success. According to [18], there are ten practices considered the best for teaching math and science. These include: use of manipulatives and hands-on learning; cooperative learning; discussion and inquiry; questioning and conjectures; justification of thinking; writing for reflection and problem solving; use of problem-solving approach; integration of technology; teacher as a facilitator; and use of assessment as a part of instruction. In addition, understanding students' misconceptions also supports teachers' pedagogy [10,19].

The research literature indicates that providing effective technology PD to STEM teachers has a positive effect on teacher and student learning [20]. However, with the exception of a few studies (e.g., [15,21]), there has been limited research on examining the outcomes of PD programs for middle school teachers implementing robotics-based STEM lessons. In addition, PD programs often do not sufficiently address the significant challenge of managing classrooms and robots and thus may fail to meet their objectives. That is, when PD participants are not adequately prepared for implementing robotics-based lessons in classroom settings, they may respond to real-world classroom challenges sub-optimally. Furthermore, PD programs with a focus on preparing participants to implement robotics-based STEM lessons in K-12 classrooms are often inadequate since they lack proper support structures, formal guidelines, and effective pedagogical approaches to promote the achievement of desired outcomes.

The LEGO Mindstorms robot kit is widely used in K-12 STEM education. For example, in one recent effort [22], it was used as a technological tool to aid in the pedagogy of physics, biology, and math lessons, resulting in teachers' readiness to implement technology as a pedagogical tool in their classroom. The researchers in [22] claimed that a robotics-based learning methodology helps students readily visualize and access abstract STEM content knowledge. Recent studies have additionally explored varied pedagogical methods for STEM learning with robotics, e.g., scaffolding [23], visual modeling [24], and project-based learning [25,26], among others.

Assessment of students' progress in learning STEM concepts is essential to analyze, retain, and enhance their motivation and impart continuous improvement. As two sides of the same coin, assessment and learning are critical to all learners for gaining a high level of understanding in the subject matter [27]. Thus, it is incumbent upon teachers to provide meaningful learning experiences to their students and measure the learning outcomes through well-aligned assessment tools [27]. Both formative and summative assessments are used by teachers to assess student progress in the classroom. Of these two, as part of the instructional process, formative assessment helps to acquire information needed to formulate better teaching and learning strategies [27]. Alternatively, summative assessments are given periodically to determine the students' progress and improvement [27]. Currently there is limited research related to the use of these different assessment methods for teaching and learning with robotics-aided STEM lessons.

Another important element of engendering a successful experience with robotics in a classroom is to aid diverse learners with what they are supposed to achieve [28]. With all the possible benefits of incorporating robotics in STEM education, it is important to ascertain how teachers can effectively integrate robotics in STEM education. Finally, proper classroom management methods constitute an essential teaching practice for successfully implementing robotics activities in the curriculum. In fact, issues related to classroom management methods are a central concern for teachers considering incorporation of robotics-based learning activities [29].

3. Theoretical Framework

Constructionism [30,31], aligned with cognitive learning [32], is a theory about learning within a community while creating and interacting with materials and technological tools. Moreover, it provides a framework for instructional design and classroom pedagogy [33]. Constructionism posits that people are able to learn best when they actively engage in self-construction of knowledge structures and come to understand its connected nature [30]. Specifically, as people seek to explore, build, test, and share new ideas, they interact with materials, tools, and other people for designing and constructing digital or physical artifacts [30]. Learning by doing in this manner affords people flexibility, motivation, imagination, and empowerment over their learning environment and knowledge construction tasks [34].

People are particularly effective in constructing new knowledge when they are permitted to engage in constructing products that are of personal meaning and relevance to them (e.g., a digital world, a 3D-printed object, a robotics device, a computer game, etc.). While creating such products, learners can actively engage with diverse stakeholders, e.g., teachers, parents, other students, etc., to engender broader support, feedback, and appreciation for their creation [33]. In this manner, constructionism supports learning through both the personal, cognitive processes of knowledge creation and the social aspects of participatory learning culture [30].

Different categories of constructionism include social constructionism [34], cultural constructionism [34], and distributed constructionism [33], among others. In this paper, we adopt the learning theory of distributed constructionism that extends the constructionist theory to address scenarios wherein multiple learners collectively engage in the design and construction activities [33]. Specifically, distributed constructionism is conceived of as integrating the concepts of constructionism and distributed cognition and [33] suggests one instantiation of it wherein computer networks support learners' collaborative design and construction activities. According to [33], distributed constructionism serves as an effective theoretical framework to create, nurture, and sustain a knowledge building community. Specifically, activities under distributed constructionism entail communicating, sharing, and collaborating about the design and construction of meaningful artifacts [33]. In the study of this paper, we employed the LEGO Mindstorms EV3 kits [35] as a technological tool to support a novel and physical implementation of distributed constructionism.

4. PD Program

Teacher effectiveness is crucial for successful classroom teaching and learning. To improve the technical and pedagogy knowledge of in-service middle school teachers for conducting STEM lessons using robotics, we designed and implemented a PD program. From middle schools in New York City (NYC), 23 teachers were recruited and engaged to learn and practice the design, development, and implementation of robotics-based STEM lessons for classroom usage. The three weeks long eight-hours per day PD program, conducted at the NYU Tandon School of Engineering, was led by engineering and education faculty who mentored graduate students and postdoctoral researchers to: develop robotics-based STEM lessons, conduct the PD sessions, and support varied instructional and feedback activities during the PD. The PD program included an array of foundational learning theories, robotics fundamentals, and robotics-based math and science lessons. Each morning and afternoon session included a short formal introductory lecture followed by hands-on learning activities that allowed exploration and reinforcement of the sessions' material. For hands-on activities, two-person teams were engaged in the robot design, programming, and lesson implementation activities. The project team facilitated the PD through varied instructional modes, e.g., lectures, hands-on learning, group discussions, insight sharing, construction and programming projects, co-generation dialogues, assignments, brainstorming sessions, competitions, challenge question and answer sessions, etc. The participating teachers were supported in performing and completing tasks by providing individualized attention on an as-needed-basis.

As mentioned above, the PD program utilized the LEGO robotics kit. All participants were provided a set of printed instruction materials on building a base robot using several specific pieces of their robot kits. LEGO Mindstorms' block-based programming method, which is relatively simple as compared to other text-based programming languages, was formally introduced to the participants. Throughout the PD, the participants learned different robotics components and concepts, including, structural elements, mechanisms, sensors, actuators, assembly, and programming. In addition to the basic robotics related concepts, the participants also learned how to employ the robotics platform to address diverse math and science concepts. Some illustrative robotics-based lessons addressed concepts such as energy, least common multiplier, modeling, number line, functions, rover, statistics, tug of war, and algebraic expressions. For further details of the PD program, see [15,21].

At the end of the PD, the research team verified that the teachers had become self-sufficient to teach robotics-based science and math lessons in their classes. To assess the confidence and self-efficacy of teachers, the research team conducted a post-program survey. In the survey, teachers were inquired about their confidence, motivation, teaching effectiveness, and interest in classroom teaching of robotics-activity based lessons. A total of 20 teachers responded to the survey of whom 17 teachers strongly or somewhat agreed that the PD participation increased their confidence as a teacher. Moreover, 18 teachers strongly or somewhat agreed that the PD participation increased their motivation to teach robotics. All teachers strongly or somewhat agreed that the PD program increased their effectiveness in teaching with robotics. Finally, all teachers strongly or somewhat agreed that the PD participation increased their interest in classroom teaching with robotics. These results demonstrate that teachers acquired self-sufficiency to teach robotics in the classroom.

Following the PD program, during the academic year, participating teachers taught robotics-based math and science lessons to students as part of their regular academic curriculum. To build their students' technical foundations for performing robotics-activity based lessons, teachers introduced the LEGO robotics kit to them. The students learned about the functionalities of different mechanical parts of the robot, building of the robot structure, applications of various sensors and actuators, and basics of the robot programming. Moreover, they learned to define problems, develop solutions, and optimize solutions, concepts that constitute the critical components of the engineering design process (EDP) incorporated in the Next Generation Science Standards (NGSS) [36]. The students also defined problems, formulated questions for scientific inquiry, constructed explanations based on observations, and designed solutions, all of which are the part of the Science and Engineering Practices (SEPs) of NGSS [36]. They performed robot troubleshooting while conducting activities, changed and incorporated various mechanical components, and performed mathematical calculations to integrate various sensors and actuators in their designs. Often, the students had to iteratively refine their solution strategy by performing the above activities multiple times if the robot did not respond according to their initial expectations. Through iterative redesign, the students came to learn how to overcome frustration and persevere. Moreover, the integration of different scientific inquiry and engineering design activities in the classroom significantly contributed to the improvement in students' skillset in STEM disciplines.

During the academic year, *each* participating teacher from the PD implemented at least five robotics-based science and math lessons. These robotics lessons were delivered to over 950 students who had not been exposed to robotics previously. The project's researchers visited the PD participants at their schools weekly to observe the classroom implementation of robotics-based lesson. Moreover, researchers supported the participants to: conduct lessons, help troubleshoot any hardware and software issues faced during lesson implementations, and carry out class discussions about robotics-based lessons. As delineated below, researchers created two questionnaires to understand and differentiate between teachers' instructional practices with robotics and non-robotics lessons. Next, the researchers needed to identify one science and one math teacher for careful observation of their instructional practices with and without the use of robot. To do so, researchers reflected on the PD program and collectively identified one science and one math teacher who had performed exceptionally well throughout the PD program.

5. Brief Description and Implementation of Lessons

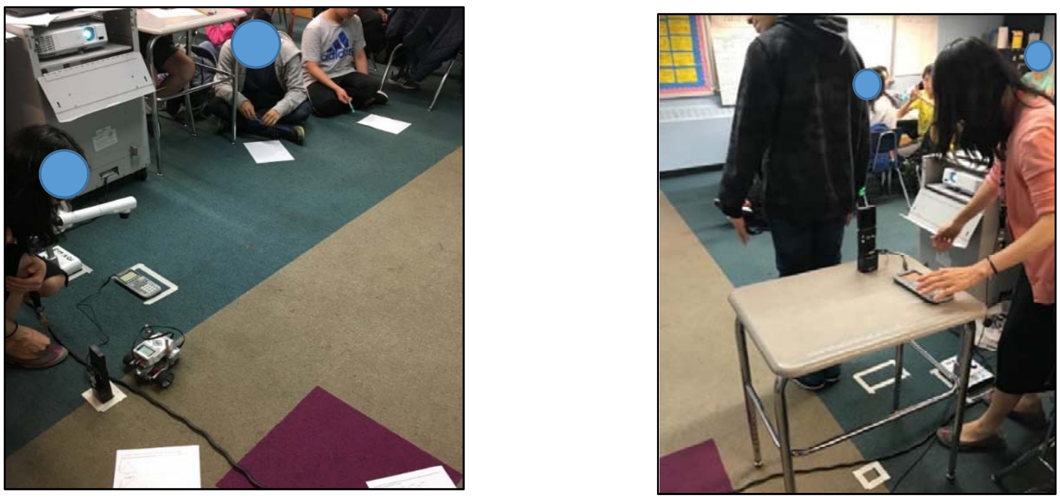
Two lessons described below were used in this study. The contents and classroom implementations of the lessons are briefly characterized below. Each lesson's math or science content was implemented using two methods: a robotics and a non-robotics activity. The two methods were conducted in the same grade-level but in different classrooms. The teachers selected the grade-level and students with whom the lessons were implemented. Moreover, each teacher created a pre- and a post-test to measure and analyze the learning outcomes of students in both the robotics and non-robotics activity classrooms. The researchers and teachers brainstormed collectively to identify a science and a math lesson for classroom implementation. They selected lessons that were new and had not been previously implemented in classrooms. The selected lessons had been designed for alignment with the prevailing school science and math curricula and with the pertinent national standards (e.g., the Next Generation Science Standard and the Common Core Math Standard). The two lessons highlighted below were selected for the following reasons: (1) these lessons contain useful concepts in science and math; (2) they provide opportunities to teach the underlying science and math concepts with robotics and non-robotics activities; (3) these lessons offered a right combination of math and science topics; and (4) the researchers and teachers collectively identified these lessons to be pedagogically challenging if not taught using an activity.

Note that the lessons with robotics activities facilitate the incorporation of distributive constructionism [33] *naturally* since robotics lessons support group leaning, knowledge-sharing, discussion, and collaboration, all in an effective and flexible manner, to improve student learning and understanding. In contrast, lessons with non-robotics activities may or may not be amenable to support physical implementation of distributed constructionism. In the study of this paper, the lessons with non–robotics activities were used only to make comparisons *vis-à-vis* lessons with robotics activities. The lessons with non–robotics activities were not specifically designed to incorporate distributive constructionism.

***5.1. Linear relationship and analyzing the pattern of a graph*:** Linear relationship is a difficult math topic for students. The teacher had previously noticed that students had many misconceptions regarding the linear pattern of a graph. Moreover, some students were not motivated to solve these kinds of problems and would often simply guess answers. However, a solid understanding of this concept is vital because students will face its many practical applications in their daily lives and in their future education. The researchers and teachers brainstormed about the lesson and identified two activities for the robotics and non-robotics activity classrooms. Prior to the lessons, the teacher conducted a pre-test to understand students' prior knowledge of the lesson's concepts. Following the lesson, the teacher conducted a post-test to measure the learning outcomes of students.

5.1.1. Lesson with robotics activity: For the robotics activity, a basic differential drive mobile robot was designed and used. In addition to the robot, a motion sensor was used to record the robot's distance from the sensor. This lesson addressed the concept of "change of the pattern of the graph." In creating and analyzing such graphs, students usually have problems identifying the independent and dependent variables and their graphical representation. This lesson can be used to reinforce the concepts of how to draw a graph concerning the motion of an object. The lesson consisted of two activities. For the first activity, students were divided into groups of three and each group was given a worksheet with four graphs. The teacher had pre-programmed the robots to perform different motions and students were to run these programs and observe and record the movement of their robots. After the observations, students had to identify the graph corresponding to each movement of their robots and write a brief description of the movement. For the second activity, students sat together as a single group, and a motion sensor was placed in front of one robot. The motion sensor was setup to capture the movement of the robot and display its graphical representation on a screen using a projector. The students were asked to compare the graphical representations of robot movements obtained from the motion sensors with their previous predictions and determine if their predictions were correct. Figure 1(a) shows the robotics activity lesson implementation in the classroom.

5.1.2. Lesson with non-robotics activity: For the non-robotics activity, instead of the movement of a robot, movements by a person were observed. The lesson consisted of two activities. For the first activity, the teacher distributed a worksheet with four graphs to all the students. Next, a co-teacher performed a series of walking movements similar to the robot and the teacher instructed the students to identify the graph corresponding to each walking movement performed by the co-teacher and write a brief description about their findings. For the second activity, all the students in the class sat together as a group and a motion sensor was placed in front of the class. Now, as the co-teacher performed the same series of walking movements as previously, the motion sensor captured the movements and displayed their graphical representations on the screen. Next, all students were tasked with comparing the graphical outputs obtained using the motion sensor with their previous predictions and determine if their predictions were correct. Figure 1(b) shows the non-robotics activity lesson implementation in the classroom.

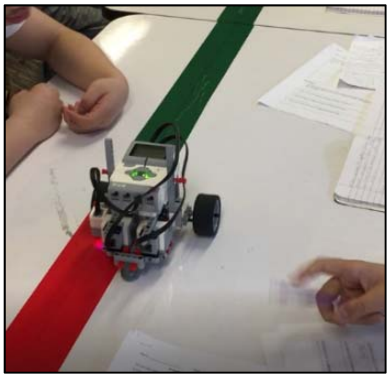


(a) (b)

Figure 1: Classroom implementation of a math lesson using (a) robotics and (b) non-robotics activities.

***5.2. Relationship between wavelength and frequency*:** The primary objective of this lesson was to enable students to learn and understand the wavelength-frequency relationship of light. The students were provided instruction about the light spectrum, different components of light spectrum, and why the red color is used for the STOP sign, etc. The lesson was implemented with a robotics and a non-robotics activity. Pre- and post-tests were used to measure student learning outcomes.

5.2.1. Lesson with robotics activity: The robotics activity employed a basic differential drive mobile robot that was instrumented with a color sensor to identify and distinguish between different colors. Red and green color masking tapes were pasted on the desk of students and a start position was marked where the students were expected to place their robots at the start of activity. The students were guided to place their color sensor vertically downward to face the color tape. Each robot was programmed such that its speed would reduce (or increase) when the color sensor detected the red (or green) color tape. Next, the students were divided into groups of four and were given a worksheet to write their observations during the robotics activity. They were tasked with running the program and observing the movement of the robot with respect to the tape. They wrote down their observation in the designated column of the worksheet. In addition, students were asked to answer several questions based on their observations. Figure 2(a) shows the robotics activity lesson implementation in the classroom.



(a)

(b)

Figure 2: Classroom implementation of a science lesson using (a) robotics and (b) non-robotics activities.

5.2.2. Lesson with non-robotics activity: The non-robotics activity consisted of three colored pencils (one each of red, green, and violet colors), an adding machine tape roll, a masking tape, and a manila folder. The activity began by tasking students to prepare tape from the adding machine tape roll for the experiment as delineated below. First, they were asked to unspool some tape from the adding machine tape roll and draw on it a vertical line (across the tape width) 20 cm from the beginning of the tape and label it as 'Start.' Second, they were asked to unspool some more tape from the adding machine tape roll and draw on it a vertical line 100cm away from the Start line and label it as 'End.' They were to confirm that at least 20 cm length of the adding machine tape was left over beyond the End line. Third, they were asked to draw three equally-spaced horizontal lines along the tape from Start to End, with the colors red (closer to the top edge of the tape), green (in the middle of the tape), and violet (closer to the bottom edge of the tape). Fourth, they were asked to subdivide the red line every 14 cm with a mark of dark red dot, green line every 10 cm with a mark of dark green dot, and violet line every 8 cm with a mark of dark violet dot. Fifth, the students were asked to insert a pencil to serve as a roller for holding the adding machine tape roll, spool the previously unspooled tape on the roll, and fasten the adding machine tape's free end to another pencil using the masking tape. Having prepared the adding machine tape for the activity, the students were asked to hold down a manila folder using a book such that the manila folder would open up along its folded crease while its free edges were weighted down under the book. Next, the adding machine tape roll was set on one side of the manila folder while its free end, fastened to pencil, was passed through the entire length of the manila folder so that it exited on the other side. One student was assigned the task of pulling the tape at a constant speed through the folder, one student to hold the pencil firm to allow the adding machine tape to unspool, one student to track and record the time, and several other students to count the number of red, green, and violet dots as the unspooling tape exited through the manila folder. Three trials of the above experiment were performed by each team and all data was recorded on the worksheet using which students found average values of colored dots seen and computed the corresponding frequency. Figure 2(b) shows the non-robotics activity lesson implementation in the classroom.

6. Research Description

Throughout this research, various types of data was collected and analyzed to perform different types of studies.

6.1. Surveys for collecting teacher's response: Two surveys were created to solicit teachers' opinion about the implementation of and student engagement in science and math lessons with (a) robotics and (b) non-robotics activities. The two surveys were administered to over 20 teachers—16 teachers responded to both surveys and one to only the survey for robotics activities. The teacher survey questionnaire inquired about students' misconception about various science and math lesson topics, how teachers used robotics or non-robotics activities to address misconceptions, different assessment methods teachers' used in robotics-activity based classroom, and student engagement. Related questions on the survey included: "What is an important lesson you implemented in the classroom using robots as a tool and why?"; "How do you identify a lesson that is well suited for robotics activity?"; "What differences, if any, do you see in robotics *vs.* non-robotics lessons?"; and "How do you ensure that your students engage in the classroom with robotics activities?". The responses from teachers to these surveys were analyzed qualitatively.

6.2. Survey to identify classroom management techniques: A survey was utilized to collect data from a subset of teachers (four) about their classroom management techniques when conducting lessons with robotics activities.

6.3. Student learning impact of lesson with robotics-activity: Two (one science and one math) teachers were the part of this study. Lessons outlined in Section 5 were implemented in two science and two math classrooms of same grades and instructed by the same teachers. The math teacher implemented the math lesson with robotics-activity in one classroom and with non-robotics activity in another classroom of the same grade. Similarly, the science teacher implemented the science lesson with robotics-activity in one classroom and with non-robotics activity in another classroom of the same grade. To identify the impact of lessons with robotics-activity on student learning, pre-/post-tests of student learning were conducted for one math and one science lesson with robotics and non-robotics activity classrooms (88 students). The assessment used for the pre/post-tests included identical multiple choice questions. Specifically, the pre-/post-tests for math and science consisted of five and six, respectively, multiple choice questions. The two teachers who participated in the study developed the questions for pre-/post-tests based on their content knowledge and they did not share the tests with researchers to prevent any potential bias. Moreover, the pre-/post-tests were administered and graded by the teachers. Table 1 summarizes details of the participants of pre-/post-tests. Since all students are from the same grade-level, their age, gender, or demographic information were not considered. Finally, researchers maintained logs of classroom observations to record activities performed by the two teachers and their students.

Table 1: Summary information about participants of pre-/post-tests.

	Subject	Student's grade level	Number of students in robotics-activity lesson	Number of students in non-robotics-activity lesson	Number of test questions
Teacher 1	Science	7^{th}	22	21	6
Teacher 2	Math	7^{th}	20	25	5

The following are the research questions for this study. (1) What are the successful teaching practices enacted by the teachers in the classrooms with robotics and non-robotics activities? (2) What are the various classroom management techniques used by the teachers in the classrooms with robotics activities and how do students respond to them? (3) What, if any, is the positive impact on student learning in the classrooms with robotics *vs.* non-robotics activities?

To design the teacher surveys, the researchers collectively brainstormed and determined various themes and related questions best suited for identifying and analyzing the successful teaching practices for conducting classroom activities with robotics. The designed survey was distributed to all teachers who attended the PD program. Moreover, data was gathered from four teachers about their classroom management techniques when conducting robotics activities and how the students respond to such techniques.

7. Results of Surveys and Tests

Using teachers' responses to surveys discussed in Section 6, we uncovered a number of themes that are categorized below to suggest different factors that constitute successful teaching practices in conducting lessons with robotics activities. This data was analyzed qualitatively. We supplemented this data with students' learning impact of lessons with robotics-activity as described in subsection 6.3.

7.1. Teachers' awareness of student's misconception:

The survey responses allowed the identification of various misconceptions of middle school students. Moreover, survey responses also indicated that teachers deemed robotics activities to be highly relevant to address these misconceptions. Table 2 summarizes teachers' survey responses concerning several science and math misconceptions exhibited by their students. As one illustration, a teacher who had implemented a lesson on cell division by using a robotics activity informed: "Before using robotics activity the students had some difficulty understanding the progression through the different steps of cell division. It seemed very abstract to them. With the robotics activity, they became more aware of different steps and what occurred in the cells at each step. These hands-on robot technologies facilitated a better understanding of the concepts."

To elaborate further, for eliminating student's misconception of cell division, the teacher used a robotics activity. Recall that the process of cell division has four different phases whose durations vary considerably depending on the activity of the cell in a specific phase. A typical rapidly proliferating human cell takes a total cycle time of 24 hours to divide and replicate. For the robotics activity, to represent 24 hours, students used a one-meter long masking tape and taped it on the center of a table. They marked the start and stop points at the two ends of the masking tape and placed their robot at the start point and executed a program. The program moved the robot at a constant speed along the length of the tape to step through each phase of cell division. The four phases of cell division were modeled by four length segments of the masking tape, with each segment being of a different length. At the end of each phase of cell division, the robot would stop briefly to represent the completion of that phase, which had to be labeled by the students. The time taken to complete each phase by the robot varied based on the duration of that phase. After completing the activity, students measured the distance traveled by the robot in each phase and converted it into phase duration in hours. From this activity, students came to understand the progression of each phase of cell division, as well as its shortest and longest phases. Next, to address students' misconception of cancer cells, the aforementioned cell division activity was altered as below. Specifically, the program was modified so that for normal cells, in addition to stopping the robot to represent the completion of a phase, for three of the four phases, the robot would also stop to represent checkpoints for the corresponding phases. Now the students had to label both the checkpoints and the completion points for various phases. If a robot stopped at the three checkpoints, it represented the model of a normal cell. However, if a robot skipped the three checkpoints and moved quickly, it represented the model of a cancer cell. Through experimentation with robots running different programs and performing observations, students were tasked to differentiate the motion of the robot as representing a normal *vs.* a cancer cell. Throughout the activity, students made predictions, shared their rationale, discussed in their groups, and recorded observations and conclusions in worksheets.

Table 2: Science and math misconceptions in the classroom.

Science misconceptions	**Math misconceptions**
Life science – Lack of understanding of the concept of cell division, specifically that cell division entails a progression of steps. – Cancer cells are foreign, not belonging to body cells (lack of understanding that the cancer cells are body cells that have lost their ability to carry out normal cell division). – Lack of understanding that diffusion is net movement of particles from high to low concentration (not a result of particles breaking down or forces acting on particles). Earth science – All planets in our solar system are equal distance from each other (lack of understanding that the planets in our solar system are not equi-distant from each other). Physical science – If an object is at rest, there are no forces acting on it (lack of understanding that an object can maintain a state of rest if there are non-zero forces acting on it that yield zero net force on the object). – If the net force acting on an object is zero, then it must be at rest (lack of understanding that when an object is subject to a zero net force, it maintains its state of motion). – Acceleration results from a change in speed of an object moving in a fixed direction (lack of understanding that acceleration results from change in magnitude and direction of speed). – Driving a vehicle is easier at a surface with less friction (lack of understanding that a surface with less friction does not mean an easier drive, especially on an incline plane) – Energy cannot be transformed from one form into another (lack of understanding about potential-kinetic transformation of energy in a pendulum and chemical-mechanical transformation of energy in a clock, etc.).	Arithmetic – Application of addition and subtraction operations with negative integers. $-6 - (-5) = -11$ (instead of $-6 - (-5) = -1$) – Base and exponent rules are misapplied as $2^4 = 2 \times 4$ and $(2+5)^2 = 2^2 + 5^2$ instead of $2^4 = 2\times2\times2\times2=16$ and $(2+5)^2 = 7^2 = 49$ – Difficulty understanding the concept of least common multiplier of two given integers (smallest non-zero number divisible by the two given integers) Algebra – All functions are linear (lack of understanding that a functions may have linear or nonlinear behavior) – Difficulty in understanding independent and dependent variables in a graph and slope of a linear graph – Difficulty in understanding the concept of ratio e.g., 1:3 = 3:1 (but in reality $1:3 \neq 3:1$) –

7.2. Identification of lessons most suitable for robotics activities:

The responses to surveys provide opportunities to identify myriad criteria teachers have considered in selecting lessons for integrating robotics in their instruction. First, the hands-on engagement in learning with robotics was deemed to facilitate a better student understanding of lesson concepts. Second, the use of robotics allowed students to connect their classroom math learning to real-world applications and appreciate its value to their future education and careers. Third, abstract science concepts that are not easily visualized with traditional instructional methods were deemed particularly suitable for robotics activities. Fourth, integration of robotics in classroom was considered additionally effective in building and honing students' leadership and teamwork skills. Finally, robotics activities were not deemed to be universally applicable for all science and math concepts. Additional methods that teachers used to identify the suitability of robotics lesson are summarized in Table 3.

Table 3: Methods used to identify the suitability of robotics lessons.

S. No.	Methods used to identify the suitability of robotics lesson
1.	Analyze various aspects of a lesson to establish if a robot can perform a role to effectively contribute to the lesson's objective.
2.	Assess and ensure that the robotics activity is appropriate for the grade level and aligns with the learning standards.
3.	Lessons that entail development and application of students' problem-solving strategies may be particularly apt for incorporating robotics activities.
4.	Examine and consider the capability of the robotics activity and how it may enhance student understanding.
5.	Identify whether a lesson needs a visual representation or increased level of engagements.

***7.3. Student engagement and motivation*:** We briefly describe several responses to this theme.

7.3.1. Differences in robotics vs. non-robotics activities: All teachers agreed that robotics-based lessons improve student engagements in the classroom, since robots are incredibly engaging to students, and consequently increase their motivation to perform the lesson activities and gain an understanding of the concepts of the lessons. Teachers reported that they observed various differences regarding student engagement and motivation for robotics *vs.* non-robotics activities. See Table 4 for a summary of responses obtained from surveys.

In addition to the details provided in Table 4, four teachers specifically indicated that their more than 30 students with special learning needs were more engaged and motivated to perform the robotics activity, thus meting the guideline of [28] for aiding diverse learners. The researchers also observed this to be the case.

Table 4: Differences in robotics *vs.* non-robotics activities.

S. No.	Differences in robotics *vs.* non-robotics activities
1.	As students understood abstract concepts better with robotics activities, they devoted more time on task.
2.	Many students exhibited a higher level of engagement in classrooms with robotics activities. Students who found it difficult to stay attentive during traditional classroom instruction tended to be more engaged with robotics activities and grasped the lesson concepts easier.
3.	Since students had more time to interact with one another doing the group work, they supported one another to stay on task.
4.	Often if students deem certain science and math concepts to be abstract, they may lose interest and motivation in the same, however, robotics activities imparted a visual understanding for such concepts and helped retain and sustain students' interest
5.	Some students engaged in problem-solving and asked more questions during robotics lessons.
6.	Student enthusiasm and motivation was more in robotics activity based classroom than non-robotics activity based classroom.
7.	Since students remained motivated when using robots, they focused on performing assigned tasks, and engaged in deep learning.
8.	With robotics lessons students learned to tolerate a level of frustration arising from the failure of robot or the program to function as expected, thus contributing positively to their behavioral development (e.g., problem-solving with patience and calm during adversity). As an example, even with occasional mechanical failure during robotics lessons, students remained involved in their learning.

7.3.2. Teacher's approaches to ensure the student engagement in the classroom: Teachers followed various approaches to ensure that their students stayed engaged in the robotics activity classrooms. See Table 5 for a summary of responses obtained from surveys.

One of the participating teachers informed: "The way I ensure my students are engaged in the robotics lesson is that before the lessons I assign all students to different teams. Each team is responsible for completing the challenge, by making sure all students work collaboratively, empowering them to take ownership by taking turns, and assuming the necessary roles such as team leader, chief assembly engineer, chief designer, chief inventory manager, etc. This ensures that all students are engaged, participate, and rotate through all functions, so all members of the team share in all different roles. It is exciting to see them taking up the roles naturally, without teacher input, and guarantees that the challenge is accomplished." The above statement indicates that by learning through lessons with robotics activities, students work with a degree of independence and accountability.

Table 5: Approaches teachers used in the classroom to ensure student engagement.

S. No.	Multiple approaches teachers used in the classroom to ensure student engagement
1.	The teachers divided students into small groups, assigned each group member a specific role to play in the activity.
2.	Explicitly explained to students why the robot was needed to be used and its specific purpose for the lessons.
3.	Alerted students that the robotics activities and their assigned tasks were part of their class grade to ensure that students understood their responsibility to complete their tasks.
4.	Ensured that students were accountable to one another and the teacher for finishing their assigned tasks.

***7.4. Assessment of student's progress*:** This subsection reports on the types of assessment methods used by teachers to monitor student learning during lessons with robotics activities and how these differ *vis-à-vis* assessments of lessons with non-robotics activities. Teachers reported (and were observed) using varied assessment techniques during lessons with robotics activities. For example, one teacher responded on the survey that each robotics-based lesson had been designed for alignment to a scoring rubric focusing on learners' social skills to collaborate and analytical abilities to comprehend and complete scientific, mathematical, design, and analysis tasks. Table 6 summarizes methods used to assess student learning with robotics-based lessons.

Table 6: Different assessments used in robotics-based lessons.

S. No.	Different assessments used in robotics-based lessons
1.	Entrance and exit tickets
2.	Pre- and post-tests
3.	Online assessments
4.	Observations
5.	Follow-up questions
6.	Self-assessment surveys and checklists
7.	Completion of assigned tasks independently or with additional support
8.	Quality of hands-on activities, data collection, and analysis
9.	Quality of student responses on assigned worksheets

Teachers also used varied assessment methods in classrooms with non-robotics activities. Nonetheless, traditional and formal assessment methods were more commonly used in classrooms with non-robotics activities. None of the teachers mentioned about giving homework assignments in lessons with robotics activities.

***7.5. Classroom management methods*:** We inquired from teachers about their classroom management methods and how their students responded to those. Below, we briefly narrate several responses.

7.5.1. Organize instructional binders: For each robotics-based lessons, organize instructional binders that contain detailed instructions regarding the hardware, software, activity, data collection, etc. Ensure that individual pages are placed in protective plastic covers. Teachers indicated that having such a binder is immensely helpful in classroom management because it eliminates confusion among students and encourages them to problem-solve and seek answers on their own. For example, the hardware instructions set provides students instructions for assembling and troubleshooting of hardware components. Similarly, the software instructions sets consists of different programming instructions for students. See Table 7 for additional details.

Table 7: Suggested items for instructional binders used to aid in classroom management.

Hardware instruction set	Software instruction set
– Instructions on robot construction and assembly – Images and names of various LEGO pieces and different parts of robot – Different types of gears and gear ratio – Images and names of different sensors, motors, cables, etc. – Basic problem-solving instructions, e.g., if the LEGO brick doesn't respond steps to follow	– Images and names of various programming icons and their function – First program on how to make the robot move – Names and functions of various programs, in case the LEGO brick is pre-programmed for an activity

7.5.2. Assigning roles to students: To facilitate student engagement, time-on-tasks, and discipline, it is essential that students are assigned different roles and functions to perform in their groups. Moreover, the leader of each student group should be provided precise instructions and should be held accountable to maintain and fulfill the assigned expectations for his/her team. For example, teachers reported (and were observed) to set up varied expectations for their students prior to engaging them with robotics-based lessons (see Table 8). Setting up such procedures and reiterating them to group leaders was deemed to be an effective classroom management strategy in that it provided clear expectations and responsibilities about safe handling and return of robots.

Following classroom management methods were additionally used: (1) setting up the ground rules for professionalism, creating teams, and keeping track of the robotics materials; (2) using different names to identify teams (Alpha, Beta, Gamma, etc.); (3) rotating roles among all team members ensured that all students gained a clear understanding of various functions and responsibilities within each group; and (4) making teams based on heterogeneous abilities and achievements allowed team members to learn from one another. Moreover, all teachers used worksheets specifically designed for recording observations, data, and calculations for the robotics-based classroom lessons. The aforementioned classroom management methods all proved critical in allowing teachers to successfully integrate robotics activities in their classroom teaching practice.

Table 8: Assigning tasks to students during robotics-based lessons.

S. No.	Assigning tasks to students in robotics-based lessons
1.	Wait for the delivery and completion of instructions.
2.	Take ownership of and be responsible for the robot kit provided to your group.
3.	Record the ID # of your robot kit container in your notebook and ensure that your programmable brick, sensors, and motors are all labeled with the same ID #.
4.	Count and check that you have all the robot kit components and report if you are missing any components.
5.	Five minutes prior to the end of class, organize your robot kit container—check your surroundings, including below your table, for any robot components that may have fallen.
6.	Report and document challenges or problems with the robot or activity that your group encountered.
7.	Maintain a problem and solution occurrence log in the instructional binder assigned to your group.
8.	Check the battery status of the programmable brick and charge it at the charging station as needed.

7.6. Impact on students learning with robotics vs. non-robotics activity lessons**:** Positive impact on student learning is the outcome of successful teaching practices. We sought to examine the impact of robotics *vs.* non-robotics lessons on student learning through pre- and post-tests in the robotics and non-robotics activity classrooms for both the science and math lessons. Teachers provided anonymized results of pre- and post-tests to the researchers for further analysis.

A Welch's *t*-test [37] was conducted for post-tests of robotics and non-robotics activities in the science and math classrooms and the results are shown below in Table 9. Welch's *t*-test is used to determine whether there is any significant difference between the means of two groups if sample sizes and variances are unequal between the groups. In this study, we compared the post-test results of robotics activity lessons with post-test results of non-robotics activity lessons to examine the impact of robotics activity on student learning. Since sample sizes and variances were unequal between the robotics and non-robotics activity groups (see Table 9 below), we used Welch's *t*-test. The results obtained are significant at a 95% significance level, i.e., there are statistically significant differences on student learning with the use of robotics *vs.* non-robotics learning activities.

Comparing and analyzing the results of pre/post-test shows that, for the science lesson, in the robotics activity classroom 63% of students exhibited learning gains while in non-robotics activity classroom 38% of students exhibited learning gains. Furthermore, for the math lesson, in the robotics activity classroom 30% of students exhibited learning gains while in non-robotics activity classroom 56% of students exhibited learning gains. Nonetheless, in the math lesson with robotics activity, no student exhibited any decline from pre- to post-test. See Tables 10 and 11 and Figure 3 for details.

Further examination of data for science classrooms reveals that students with robotics activity performed better than students with non-robotics activity—yielding slightly higher average on pre-test (61.36% *vs.* 57.14%) and much higher average on post-test (73.48% *vs.* 59.52%). Similarly, examination of data for math classrooms reveals that students with robotics activity performed at a relatively higher level than students with non-robotics activity both on pre-test (average 66% *vs.* 32.8%) and on post-test (average 74% *vs.* 53.6%). As evidenced above, in math classrooms, average pre-test score of students with robotics activity was double the average pre-test score of students with non-robotics activity and even higher than their post-test scores.

Table 9: Welch's *t*-test for post-test with robotics *vs.* non-robotics activities.

Lesson	Robotics activities statistics			Non-Robotics activities statistics			*t* value	*p* value
	n	Avg. %	Var.	*n*	Avg. %	Var.		
Science	22	73.48	229.076	21	59.524	599.206	2.034	0.032 (Significant)
Math	20	74.00	1183.158	25	53.60	957.333	2.023	0.045(Significant)

Table 10: Numbers of students exhibiting gains in pre-/post-tests on lessons with robotics activities.

Lesson	# of students				% of students showing learning gains
	Total	No pre- to post-test change	Increased score on post- *vs.* pre-test	Decreased score on post- *vs.* pre-test	
Science	22	6	14	2	63
Math	20	14	6	-	30

Table 11: Numbers of students exhibiting gains in pre-/post-tests on lessons with non-robotics activities.

Lesson	# of students				% of students showing learning gains
	Total	No pre- to post-test change	Increased score on post- *vs.* pre-test	Decreased score on post- *vs.* pre-test	
Science	21	6	8	7	38
Math	25	6	14	5	56

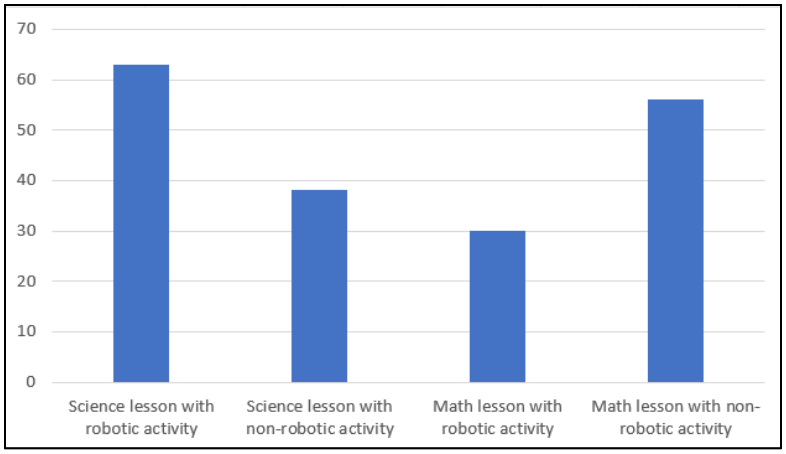


Figure 3: Comparison of percentage of students exhibiting learning gains in pre-/post-tests with robotics *vs.* non-robotics activities.

8. Discussion

By using surveys of PD participants, pre-/post-tests of students, and observations of two classroom teachers, this paper has obtained several informative results. Examination and analysis of the obtained results have helped identify several teaching practices that enabled successful integration of robotics activities in classroom science and math lessons and yielded a positive impact on student learning in contrast to non-robotics activities. Overall, post-test results show statistically significant differences in student learning with robotics *vs.* non-robotics activities. The pre-/post-test results illustrate that 63% of students show improvement in science lessons with robotics activities compared to only 38% with non-robotics activity. In contrast, for the math lesson only 30% of students show improvement with robotics activities compared to 56% with non-robotics activity. However, as evidenced above from pre-/post-test averages, students in math classroom with robotics activity had fewer opportunities to demonstrate learning gains on post-test *vis-à-vis* their pre-test. Nonetheless, it is noteworthy that no student in the math classroom with robotics activity showed any decline on post-test.

As evidenced from the two lessons (Section 5), teachers' survey responses (Section 7), and researchers' classroom observations (Section 7), the classrooms with robotics-based activities enacted the model of distributed constructionism [33]. Specifically, Papert's constructionist learning [31]—initiated through hands-on interactions with robots—was broadened with cooperative engagement of multiple learners performing activities with the robot as a learning tool. Specifically, as students worked in teams, they: shared knowledge and experiences with one another; communicated within and across teams as well as with teachers about challenges encountered and successes experienced; and collaborated to build and operate robotics artifacts for performing experiments, data gathering, analysis, etc. Thus, in contrast to the non-robotic activity lessons, the robotics activity lessons of this paper effectively embodied distributed constructionism.

As evidenced through the survey responses and classroom observations (Section 7), integration of robotics activities in science and math lessons supported multiple effective strategies for classroom teaching as advocated in [9,18]. The array of teaching practices identified above can empower teachers who may be considering classroom integration of robotics. Teachers need awareness of the common science and math misconceptions students hold [10,19]. In fact, teachers who are aware of their students' misconceptions are known to positively influence their learning gains [38]. While the same STEM concepts and principles were addressed with robotics and non-robotics activities, successful teaching requires that teachers understand student misconceptions and, we suggest, address them using robotics for enhanced science teaching and learning. Teachers' survey responses helped identify different misconceptions that students hold and how lessons with robotics activities address such misconceptions.

Educators frequently face the challenge of making abstract science and math concepts accessible and meaningful to learners. Inclusion of manipulatives and promotion of hands-on learning have been recommended as effective teaching practices [18] that have the potential to enhance math and science learning. Nonetheless, successful classroom teaching of science and math using robotics (as a manipulative for hands-on learning) requires a clear understanding that robotics is not a panacea for every STEM instructional challenge. Instead, it is essential to identify the science and math concepts that are most amenable for treatment using robotics. For example, as evidenced in the literature, robotics-based pedagogy affords kinesthetic experiences [6] and opportunities for visual modeling [24]. Thus, challenging lesson concepts ought to be carefully examined for treatment with robotics, in the aforementioned spirit, to facilitate student engagement and comprehension. Results show that abstract science and math lessons are better suited for robotics-based activities wherein robots can provide a visual representation to enhance understanding. Without robots, abstract lessons often remain abstract to students.

Integration of robotics-activity based lessons in the classroom demonstrates the operationalization of corporative learning, another successful teaching practice for math and science [18]. Students were observed to be more self-motivated and thus showed more willingness to do the robot-based activities. Moreover, during the robotics activities, the teachers circulated between students, offered appropriate level of guidance and observed their group work performance, including whether they faithfully played their assigned roles. Teachers asked different questions to the students while they worked on project and hence gauged their level of engagement in the robotics activities. Thus, robotics activities encouraged interactions between the educators and learners, one of the effective classroom practices suggested in [9]. Once students finished the activity, the teachers mediated a discussion with all students about their observations from the activity, predictions, and findings and the robotics activity's relationship to real-world applications. The aforementioned activities supported a number of successful teaching practices for math and science learning [18], including discussion and inquiry, questioning and conjectures, and teacher as a facilitator.

Integration of robotics activities in the classroom can broaden the learning experience of academically high achieving students while also engaging those who lack interest and motivation in schoolwork. During classroom observations, students were seen to be enthusiastically engaged in performing robotics activities to learn classroom science and math concepts. They were found to be more attentive in the classroom. Robotics can be successfully used for diverse student populations including those with special learning needs [28]. It was observed that students with special learning needs were especially excited to participate in robotics activities.

Teachers' use of any form of formative assessment methods (e.g., entrance ticket to test students' prior knowledge, online assessments, students group observations, and providing checklist during activities for self-assessment) improved their knowledge of student misconceptions prior to robotics activities.

Conclusions and Future Work

A cohort of over 20 middle school teachers participated in a summer robotics PD to learn about robotics as well as developing and implementing robotics-based STEM lessons for classroom teaching. Upon returning to their schools, during the academic year, these teachers implemented an array of math and science lessons most suitable for and aligned with their classroom learning goals. These teachers were surveyed to obtain their experiences and opinions about classroom learning of science and math with robotics and non-robotics activities. Classrooms of two teachers were carefully observed during the implantation of science and math lessons and student learning in these classrooms was analyzed through pre-/post-tests. Through the aforementioned activities, an array of teaching practices has been identified that supports the effective integration of robotics-based activities in science and math lessons. Teachers' concerns about classroom management challenges must be taken into consideration by PD providers when introducing new instructional approaches and embedding technological tools. Integration of practices identified above, e.g., instructional binders and assigning roles to students, ensures that students become active participants in the science and math classrooms. Such an approach additionally fosters a close-knit community where students feel responsible for their learning. Moreover, the impact of robotics-based lessons on diverse student populations was examined and it was observed that the integration of robotics enhances learning outcome for students of diverse backgrounds, including those with special learning needs. The focus of this paper on examining and analyzing successful teaching practices with robotics-based activities for middle school science and math lessons is novel. The practical application of learning theory framework of distributed constructionism illustrated participants' capacity to promote communication, sharing, and collaboration among students to promote effective learning of lesson concepts. Future work will explicitly take into consideration students' cultures and their science and math misconceptions in creating robotics-based lessons.

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