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Enriching K-12 Science and Mathematics Education Using LEGOs

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ABSTRACT

This paper presents a series of illustrative LEGO Mindstorms-based science and math activities, developed under an NSF GK-12 Fellows project, for elementary, middle, and high school grades. The activities, developed by engineering and science graduate Fellows in partnership with K-12 teachers, are grade appropriate, address pertinent learning objectives, and adhere to the science and math learning standards of New York City and State. To measure the effectiveness of the use of LEGO Mindstorms-based lab activities in science and math lessons, pre- and post-lesson assessment surveys, consisting of content and evaluation questions, were administered to all participating students. In this paper, we provide: our motivation to investigate the effectiveness of LEGO Mindstorms-based lessons; descriptions of six LEGO Mindstorms-based science and math activities and their associated assessment; statistical analysis; reflection on the effectiveness of the lessons; and recommendations for future work.

Keywords: LEGO Mindstorms-based education, assessment, conceptual understanding

INTRODUCTION

As society continues its technological advancement at an exponential rate, maintaining competitiveness in the global economy requires that students at all levels develop technology proficiency in proportion to the tempo of our changing world. In the United States, advances in technology have pervaded our daily lives and include the latest cellular phones that can generate step-by-step directions from one's location to the nearest Starbucks and vehicles with voice activated systems that allow the driver to turn on the radio, adjust the mirrors, and control temperature, without ever lifting a finger. Although today's students enjoy ready access to these technological advancements and effortlessly interact with such modern technological artifacts, they often lack a fundamental understanding of the underlying science and engineering concepts. Advancing students' understanding requires pedagogical tools and techniques with the appeal of tech-savvy devices that capture students' imagination while fostering their learning of science, technology, engineering, and math (STEM) principles. For over a decade, robotics competitions such as FIRST LEGO League (FLL) have provided a venue where students get an opportunity to explore and interact with advanced tools and devices used by engineers and technologists. In fact, on November 23, 2009, when President Obama introduced his new initiative, "To Educate and Innovate," he said, "I believe that robotics can inspire young people to pursue science and engineering."

Examples of using robotics to teach STEM concepts abound in literature and cover the entire education spectrum from elementary to graduate school [1–4]. Unfortunately, the extracurricular nature of robotics contests has not made the use of robotics more central to K-12 science and math education. Moreover, the potential for explicitly exploring science and math principles using robotics-based activities remains largely untapped in K-12 schools [5]. In fall 2010, we surveyed New York City (NYC) FLL coaches and received 43 responses (≈33% response rate). The survey results revealed that approximately 50% of respondents do not use robotics in their classrooms and only a small number provided explicit, meaningful examples of their use of robotics in STEM classrooms. Many robotics-focused K-12 programs are organized as outreach efforts for students' educational enrichment and necessitate on-site support of teachers through college-level engineering students [6] or volunteer engineering professionals [7], thereby making it difficult to sustain and scale-up projects. Therefore, increasingly, the focus of educators has been to transition students' extracurricular robotic experiences from the after-school and competition preparation programs to the classroom setting.

This paper presents several illustrative LEGO Mindstorms-based science and math activities developed under a GK-12 Fellows project of NSF at the Polytechnic Institute of NYU (NYU-Poly). Over the past four years, 27 graduate Fellows pursuing masters or doctoral studies in engineering (e.g., chemical and biological, civil, electrical, computer, and mechanical), computer science, and chemical and biological sciences have participated in this project. The activities, developed by the NYU-Poly GK-12 Fellows in partnership with K-12 teachers, are grade appropriate, address pertinent learning objectives, and adhere to the science and math learning standards of New York City and

State. In the following sections, we provide: our motivation to investigate the effectiveness of LEGO Mindstorms-based science and math lessons; descriptions of six LEGO Mindstorms-based science and math activities; overview of assessment and evaluation methods used to analyze the effectiveness of the lessons; statistical analysis and observations; and reflection on the effectiveness of the lessons, discussion of sustainability, and recommendations for future work.

MOTIVATION

In his seminal work, [8], Papert showed that children can not only learn to use computers but also that learning to use computers helps shape the way they think, learn, and understand other disciplines, e.g., math. Papert's work led to a series of investigations, such as [9–12], among others, on building children's mathematical understanding through computers. Following Papert's work, the use of modern technologies, e.g., robotics, in engaging the interest of K-12 students in STEM disciplines has been explored widely [1–7, 13–19]. Prior studies have yielded evidence that robotics-centered activities provide compelling opportunities for learning about the role of science and engineering in our society, including possible career opportunities in these fields, and life and workplace related skills, such as the ability to work with others on a team and time management [20]. Moreover, integration of sensor-based activities in science labs has led to increased student achievement in standardized tests, such as the New York State Living Environment Regents examination [21].

In this work, we have focused on integrating a variety of sensors, which are compatible with the LEGO Mindstorms NXT platform, to develop experimental apparatus that facilitate scientific explorations and broaden the use of student-friendly robotics technology [22–25]. The LEGO Mindstorms platform offers a variety of components that not only help engage students' creativity but also allow the application of teaching strategies such as scaffolding and problem-based learning. For example, judicious integration of sensors in hands-on lab activities can engage students' understanding since it allows connecting abstract concepts or textbook formulae to tangible measurements performed by students. The variety of sensors available with the LEGO Mindstorms robotics platform permits the acquisition and processing of a multitude of physical stimuli arising in science subjects that often require separate, standalone equipment. Although LEGO Mindstorms kits represent an additional cost ($300 per kit) for schools that do not participate in FLL competition, they are available in thousands of schools that do. In comparison to alternative technologies, such as pen lasers, photodetectors, and data loggers, LEGO Mindstorms are more user-friendly and less problem-prone during lesson preparation and deployment.

Although, mobile robotics can be used to illustrate and reinforce numerous science and math concepts, in practice, many K-12 robotics programs concentrate solely on mechanical design and programming aspects of the robot. Such an approach fails to exploit the motivational powers of robotics for students' science and math learning. Specifically, in science and math classrooms, robotics technology can be presented to students as a tool to perform real-world experimental investigations, hence creating a bridge between the different STEM disciplines. For example, as students develop strategies for the locomotion of a robot traveling a specified distance, they gain an understanding of the geometry of a circle, which connects the distance traveled by the robot to the circumference of its wheels. Hence, such an approach requires a departure from the traditional tri-fold robotics curricula of construction, programming, and task-oriented application to one with a stronger emphasis on the factors that influence the behavior of the robot and the data collected by it. This alternative approach allows students to focus on analyzing trends or patterns in the data and making inferences or predictions when experimental parameters are changed.

In this paper, we offer the overview and assessment of six science and math activities that employed LEGO Mindstorms-based automated lab apparatuses and robotics as a tool to enhance understanding of relevant concepts of the lessons and, in some cases, aid in the reporting of experimental data. These activities offer students authentic laboratory experiences that reinforce traditional classroom instruction, support deeper understanding of the subject matter [1, 2, 16, 17, 25], and promote active earning through discovery [14]. Additional theoretical and pedagogical justification for the approach of this paper is evidenced through Piaget's constructivism [26–28], Papert's constructionism [29], motivational aspect and problem-solving approaches supported by LEGO Mindstorms [5], versatility of LEGO Mindstorms as an experimental tool for elementary through graduate education [1–4], among others.

The six LEGO Mindstorms-based lessons were developed and conducted in elementary, middle, and high school science and math classes in several public schools in Central Brooklyn. Specifically, the three science activities, *viz.*, *The Mechanical Advantage*, *Acceleration due to Gravity*, and *Fluid Flow Rate*, were conducted in elementary school science, middle school technology, and high school science integration classes, respectively. The three math activities, *viz.*, *Measurements & Accuracy*, *Pi-What is it?* and *Means, Modes, and Medians*, were conducted in elementary school science and robotics, middle school technology, and high school algebra classes, respectively. The objective of the lessons was to teach students science and abstract math concepts, which are tested on New York State exams, through fun, engaging, and interactive hands-on LEGO Mindstorms-based activities. The GK-12 Fellows and the teachers collaborated in conducting the LEGO Mindstorms-based experiments, which were used to reinforce the state mandated learning standards, during two consecutive 45 minute class sessions. The teachers reviewed and approved each lesson for alignment with their curriculum.

Using student-friendly technology and software, the lessons promoted team-oriented and research-like environment. All lessons and corresponding evaluation instruments can be obtained by accessing NYU-Poly's GK-12 project website. Moreover, video snippets of LEGO Mindstorms-based science and math lessons in action can be viewed here. This effort has three main goals: (1) to provide concrete illustrations of the versatility of LEGO Mindstorms in teaching K-12 level science and math concepts; (2) to exploit LEGO Mindstorms-based automated lab apparatuses and robotics to facilitate automated data collection for K-12 level experimental activities that otherwise use manual, tedious, and problem-prone data collection technologies; and (3) to demonstrate through assessment that robotics can be exploited to enhance the teaching of science and math in K-12 classrooms.

DESCRIPTIONS OF SCIENCE ACTIVITIES

The Mechanical Advantage

Using the LEGO Mindstorms kit, an experimental apparatus, consisting of a wirelessly controlled mechanized elevator platform, is constructed to demonstrate the use of pulleys in producing mechanical advantage (Figure 1). Students in science labs explore the setup by adding or removing pulleys from the mechanical system, adding weights to the platform, and controlling power input to the drive motors of the platform using a custom designed controller which uses the Bluetooth feature of the LEGO Mindstorms NXT brick. Students are asked to identify the pulleys in the setup and examine the role of pulleys by operating the setup with and without pulleys. The effects of use or absence of pulleys is qualitatively assessed and recorded by students as the system's ability or inability to lift objects of a certain weight, the speed at which objects are lifted, and the tension along the strings holding the platform. This lab activity reinforces the concept of producing mechanical advantage through the use of pulleys and it promotes a more coherent and complete identification of pulleys as a simple machine.

Acceleration due to Gravity

Using the LEGO Mindstorms kit, an experimental apparatus is constructed that is used by students to measure the time to travel a specified distance by a free falling body (Figure 2). Students use a touch sensor, a rotational sensor, and two LEGO Mindstorms NXT bricks, to measure the time of flight for the falling object, at different release heights. A robotic gripper holds the object

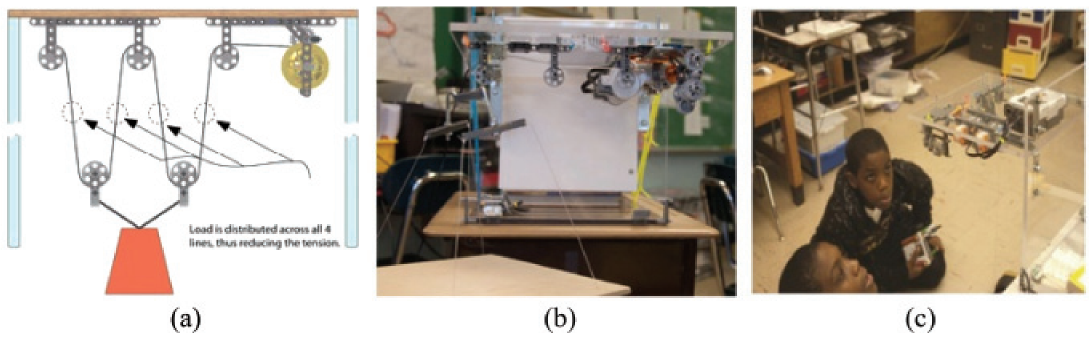


Figure 1. (a) Schematic of the pulleys setup used for The Mechanical Advantage activity; (b) photo of setup; and (c) students performing the activity.

and releases it upon receiving the operator command. When the object reaches the end-point of its travel, the touch sensor is triggered and the time of object's descent from release to impact at the touch sensor is recorded and displayed on the LEGO Mindstorms NXT screen. Moreover, using several different release points, students calculate the corresponding average velocity of the falling object. Next, they plot a graph of average velocity versus time and apply a best fit line to this graph. Finally, students determine the slope of the best fit line (one-half g) and compare it to the standard value of g (see Figure 2). This lab activity reinforces the concept of gravitational acceleration and an experimental method to determine this constant.

Fluid Flow Rate

Using a LEGO Mindstorms-based automated lab apparatus, this activity introduces students to the concepts of flow rate and its dependency on pipe diameter. A pair of LEGO Mindstorms light sensors is used in a photogate configuration. The designed setup functions in the manner of a stopwatch wherein the events are timed using the light sensor signals instead of manually operating a stopwatch (Figure 3). A plastic bottle is used as a liquid reservoir and is fitted with a nozzle at its bottom to release the liquid. Upon release from the reservoir, the liquid falls into a glass beaker which acts as a basin. As the liquid draining from the reservoir fills up the basin to the level of light sensor #1, the "stopwatch" programmed on LEGO Mindstorms is triggered to initiate timing of the event. Next, the liquid level in the basin continues to rise and triggers light sensor #2 upon reaching its level. Triggering of light sensor #2 signals the termination of the stopwatch timer. The time elapsed between the triggering of two light sensors is recorded and displayed on the LEGO Mindstorms NXT screen and used to compute the average volumetric flow rate of the system. By attaching orifice fittings of various diameters to the bottom of the bottle, students discover the

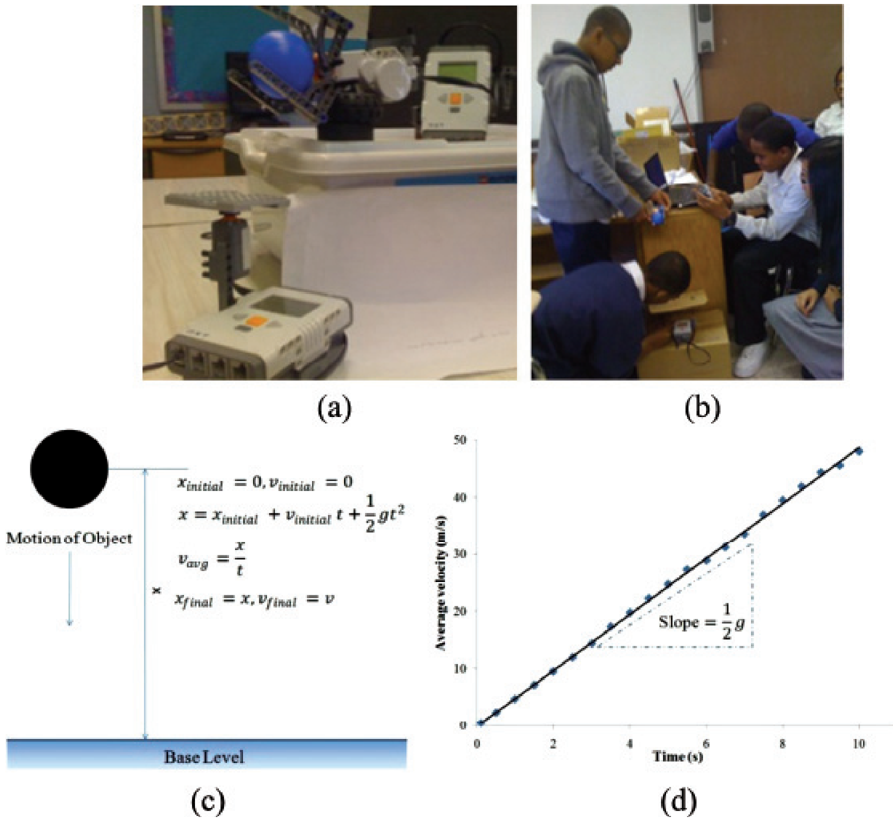


Figure 2. (a) Experimental apparatus for the Acceleration due to Gravity activity; (b) students performing the activity; (c) schematic of motion for a free falling body; and (d) plot to determine g.

effects of different diameter orifices on the average volumetric flow rate of the system. Similarly, by changing the initial level of liquid in the reservoir, students can examine the effect of initial liquid level on the average volumetric flow rate.

DESCRIPTIONS OF MATH ACTIVITIES

Measurements & Accuracy

This activity introduces students to the concept of length measurement and data organization. In particular, students are taught to take accurate measurements, understand the importance of units, organize data in ascending and descending order, and compare collected data according to

(a) (b)

Figure 3. (a) Experimental apparatus for the Fluid Flow Rate activity and (b) students performing the activity.

the length. Using a LEGO Mindstorms robot outfitted with an attachment to accommodate a pen or marker, various line segments are drawn as specified by the number of rotations of the wheels of the robot (Figure 4). For example, when the robot is pre-programmed to move forward by one wheel rotation it draws a line of approximately 7 inches. Similarly, when the robot moves by two wheel rotations it draws a line of approximately 14 inches. Using a ruler, students are tasked with measuring the length of each line segment to the nearest half inch and recording their measurements using the appropriate units (Figure 4).

Pi–What is it?

This activity was developed to promote conceptual understanding of the irrational properties of π and its applications in geometry. The objective of the activity is to create an environment in which students assume the role of researchers seeking to establish an approximate value of π and understand its relationship to circumference and area of a circle. In addition, the students review the concept of ratios as well as rational and irrational numbers through hands-on applications. Using a LEGO Mindstorms robot outfitted with an attachment to accommodate a pen or marker, circles of various diameters are drawn as determined by a pre-loaded program (Figure 5). Students are tasked with measuring the radius or the diameter of the circle using a ruler and calculating the circumference and area of the circle along with several useful ratios (Figure 5), ultimately leading to the empirical exploration of π and its properties.

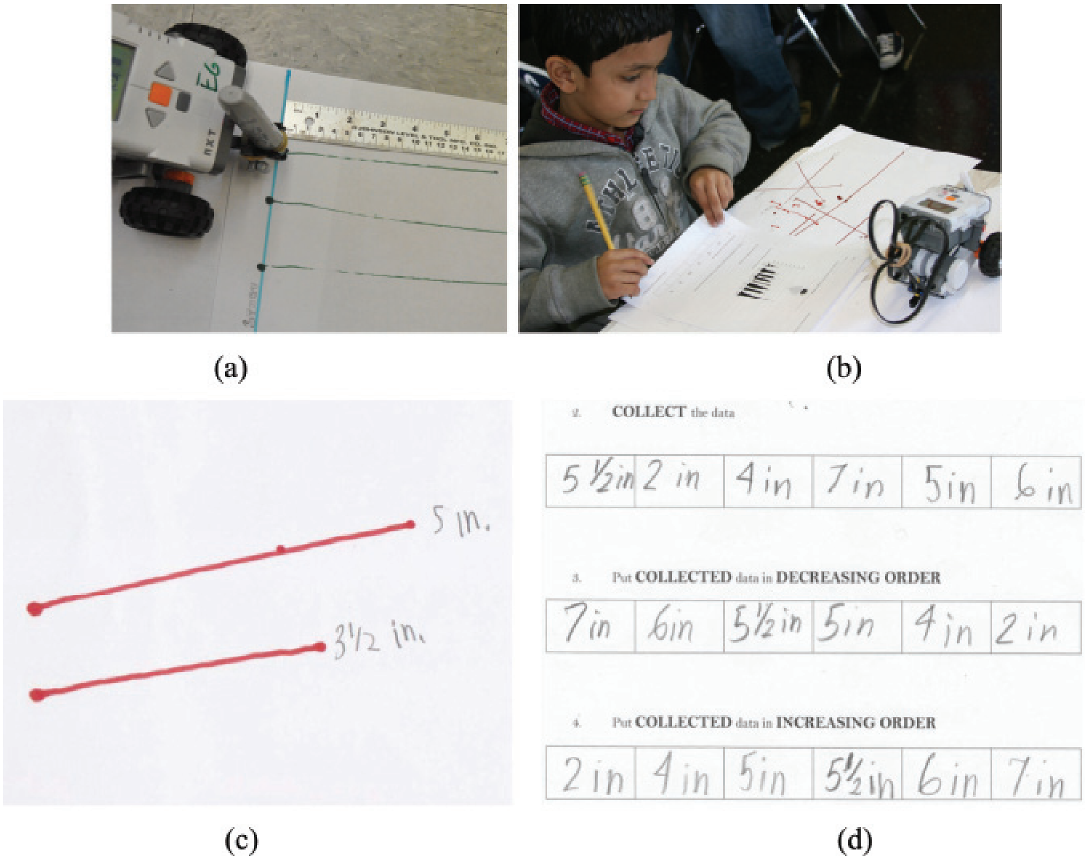


Figure 4. (a) Robotic setup used in the Measurements & Accuracy activity; (b) a student recording his measurements and filling out post-lesson evaluation survey; (c) measurements taken by a student; and (d) the table used to record and organize data during the activity.

Means, Modes, and Medians

Using a LEGO Mindstorms-based experimental apparatus, this activity introduces to students the concepts of empirical data collection and analysis. First, to produce periodic motion of an oscillating spring-mass system, a rubber band is suspended from a clamp-stand with a 1 kg mass and a cardboard platform rigidly attached to the inelastic part of the cord (Figure 6). Next, a LEGO Mindstorms ultrasonic sensor is placed on the base of the clamp-stand and above the platform to measure its distance from the oscillating cardboard platform. The data logging component of the LEGO Mindstorms software is used to record the changes in distance of the cardboard platform and output the values to a spreadsheet program for display and analysis. Students are tasked with

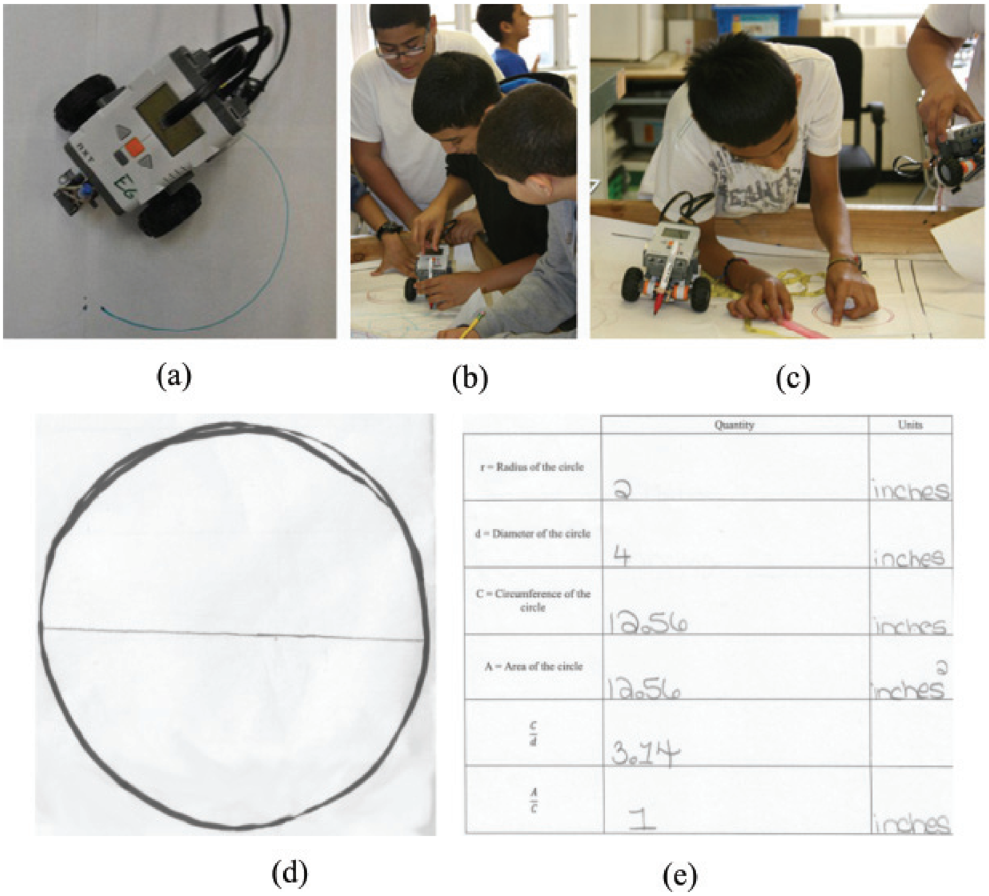


Figure 5. (a) Robotic set up used in the Pi-What is it? activity; (b) students operating the robotic device; (c) a student taking measurements with the ruler and a measuring tape; (d) the drawn circle; and (e) the table used to record and calculate data during the activity.

determining the mean, mode, and median for the collected data and evaluating the validity of the data points, such as the occurrence of outliers due to varying experimental conditions (Figure 6).

EVALUATION METHODS

To measure the effectiveness of the use of LEGO Mindstorms-based lab activities in science and math lessons, pre- and post-lesson assessment surveys (see Table 1), consisting of content and evaluation questions, were administered to all participating students immediately before

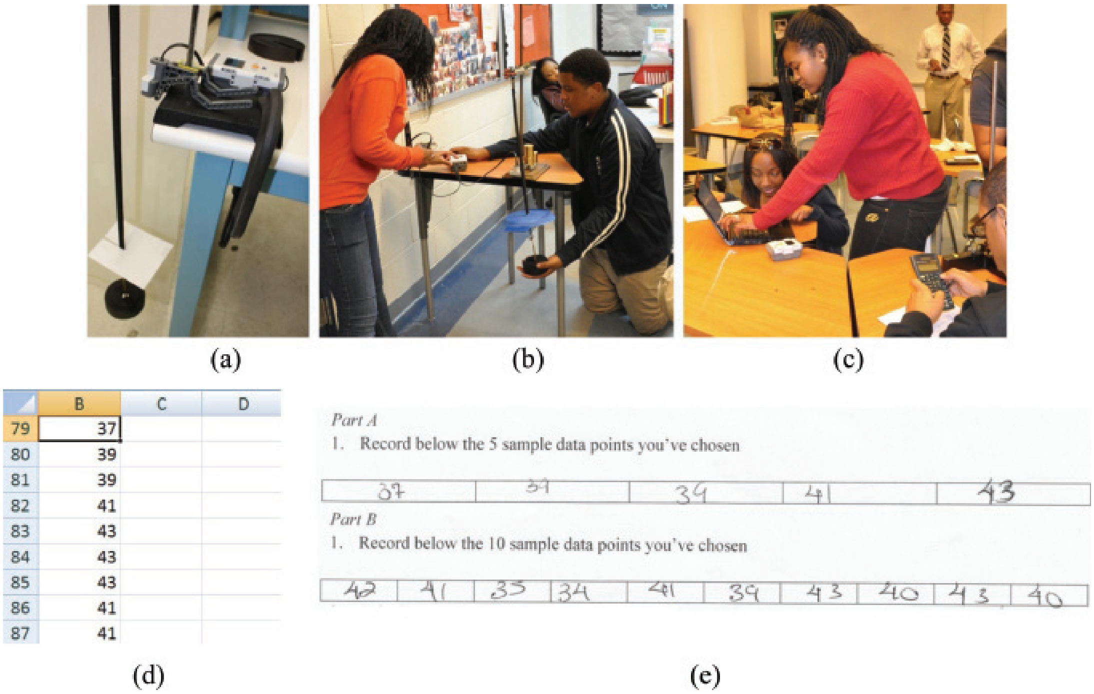


Figure 6. (a) Experimental apparatus used in the Means, Modes, and Medians activity; (b) students preparing to collect data; (c) students analyzing collected data from the Excel spread sheet; (d) data collected during the activity and presented on the Excel spread sheet, and (e) data recorded from the spread sheet.

(pre-assessment) and immediately after (post-assessment) the lessons. The assessment surveys were developed by the GK-12 Fellows in collaboration with the teachers of respective grades and subjects to be timely, responsive, appropriate, and effective for the intended students. The GK-12 Fellows also consulted with a science education expert on the appropriateness of survey questions and the development of activities to ensure that the pertinent learning standards for the subject and grade were adhered to [30, 31].

The survey utilized multiple-choice questions, fill in the blanks, and short answer essays in a student-friendly format. The evaluation questions sought to obtain information on students' perception of science and math, their prior experiences with robotics, and their opinion about the LEGO Mindstorms-based science and math lessons (Table 2). The content questions were developed by drawing upon prior years' New York City and State science and math assessment exams [32]. The content questions sought to examine students' knowledge gained through the LEGO Mindstorms-based activity

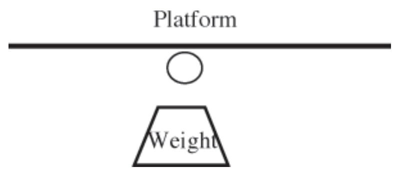
Activity	Content Questions	Learning Standards
The Mechanical Advantage Science, Elementary school	• What is a pulley and what is the purpose of using a pulley? • Draw the way pulleys can be installed on the given platform to help lift the weight shown below.  • What happens to the string when pulleys are added to them?	**PS 5.1b** Observe and describe how the position or direction of motion of an object can be changed by pushing or pulling. **PS 5.1c** Observe how the force of gravity pulls objects toward the center of the Earth.
Acceleration due to Gravity Science, Middle school	• What is a force? • What is velocity? • What is acceleration?	**PS 5.1a,b** Patterns of motion, frame of reference and position, direction, and speed. **PS 5.1b,c,d,e** Newton's Three laws of motion.
Fluid Flow Rate Science, High school	• What is flow rate? • Which parameters affect flow rate? • Give a physical example of where regulating flow rate is important and how it is regulated in practice?	**S3.1** Tools in measurement. **M2.1** Evaluating experimental results. **Standard 6–3.2** Scientific notation.
Measurements & Accuracy Science and robotics, Elementary school	• Order the numbers from smallest to largest. • Order the numbers from largest to smallest. • Using the ruler measure the height of an object in inches. • What is the difference in height between the tallest and shortest objects?	**2.M.1** Use non-standard and standard units to measure both vertical and horizontal lengths. **2.M.2** Use a ruler to measure standard units (including whole inches and whole feet). **2.M.3** Compare and order objects according to the attribute of length.
Pi–What is it? Math, Middle school	• Simplify the ratio of circumference to area. • How many digits does number π have? • Calculate the area of the circle. • What is an irrational number?	**6.G.9** Understand the relationship between the circumference and the diameter of a circle. **6.N.6** Understand the concept of ratio. **6.R.1** Use physical objects, drawings, charts, tables, graphs, symbols, equations, or objects created using technology as representations.
Means, Modes, and Medians Math, High school	• Calculate the mean. • Calculate the median. • Calculate the mode. • Solve a word problem with known average and missing data.	**A.CN.7** Recognize and apply mathematical ideas to problem situations that develop outside of mathematics. **A.S.1** Categorize data as qualitative or quantitative. **A.S.4** Compare and contrast the appropriateness of different measures of central tendency for a given data set.

Table 1: Content questions used for the LEGO Mindstorms-based science and math activities and their associated New York City and State Science and Mathematics Learning Standards.

by asking the same questions on the pre- and post-lesson assessment surveys. Questions 1–3 of the pre-lesson assessment survey were repeated in the post-lesson assessment survey for both science and math lessons. A binary-scale grading rubric (see Table 3) was used to evaluate the content

	Assessment survey questions
Pre-lesson Survey	1. What gets you excited about science/math? 2. If you were given the chance to create this lesson which method would you use: (a) Lecture; (b) Read textbook; (c) Watch movie; (d) Conduct hands-on activity; (e) Research on the internet. 3. Do you think robotics can be helpful when used to collect data in science/math experiments? (a) Yes; (b) No; (c) Unsure.
Post-lesson Survey (include 1–3 above)	4. What did you like or dislike about the lesson? 5. What did you like or dislike about the robotic device? 6. Rate this lesson using the following (a) Strongly disliked; (b) Disliked; (c) Liked; (d) Strongly liked. 7. Do you think the use of robotics to collect data: (a) Made the lesson easier; (b) Made the lesson harder; (c) Made no difference in the lesson.

Table 2: Pre- and post-lesson assessment survey evaluation questions for LEGO Mindstorms-based science and math activities.

questions as either correct or incorrect. Similarly, for survey questions that required descriptive answers, student's responses were analyzed and categorized as either Positive or Negative (Question 1) and Liked, Disliked, or No Response (Questions 4 and 5). Illustrative examples of students' descriptive responses are provided in the Data Analysis and Observations section.

The responses to survey questions were compiled and analyzed using bar charts and statistical hypothesis tests. Bar charts summarize students' performance before and after the activity. A dependent *t*-test [33] for paired samples was used to evaluate the difference in students' average scores on the pre- and post-lesson assessment surveys content questions. Moreover, a McNemar's test [33] on paired proportions was performed using the number of students that scored above and below the class average on the pre- and post-lesson assessment survey content questions. The results of both tests were used to examine the null hypothesis that no statistical difference between students' scores on the pre- and post-lesson assessments existed.

DATA ANALYSIS AND OBSERVATIONS

The science activities outlined above were assessed in two 3rd grade elementary school science classes consisting of a total of 44 students, two 8th grade middle school technology classes

Content questions	Correct responses	Incorrect responses
	The Mechanical Advantage	
What is a pulley and what is the purpose of using a pulley?	Student mentions keywords pertaining to a simple machine or a wheel in which a rope or string passes around. Student mentions how pulleys are used to achieve mechanical advantage or to lift heavy objects. Both parts of the questions must be answered by student to receive full credit.	Student provides descriptions unrelated to those in the "Correct responses" column, including: "pulleys are used to pull things."
Draw the way pulleys can be installed on the given platform to help lift the weight shown below.	Student provides a diagram in which a rope or string goes over at least one upper pulley and under at least one lower pulley in the diagram.	Student provides a drawing unrelated to the description in the "Correct responses" column that fails to yield mechanical advantage.
What happens to the string when pulleys are added to them?	Student discusses that the strings feel looser or strings are not as stiff or tight as before.	Student gives an answer unrelated to the description in the "Correct responses" column, e.g., the strings become tighter and stiffer.
	Acceleration Due to Gravity	
What is a force?	Student provides keywords pertaining to a pushing or pulling action, including making something move.	Student provides keywords or descriptions unrelated to those in the "Correct responses" column.
What is velocity?	Student provides keywords pertaining to the rate of change of position with respect to time. If the student uses the terms "fast" or "slow", they must be used together, such as how fast or slow something is going.	Student provides keywords or descriptions unrelated to those in the "Correct responses" column.
What is acceleration?	Student provides keywords pertaining to the rate of change of velocity with respect to time. If the student uses terms such as "speeding up" or "slowing down", they must be used together, such as when something speeds up or slows down.	Student provides keywords or descriptions unrelated to those in the "Correct responses" column.
	Fluid Flow Rate	
What is flow rate?	Student provides keywords pertaining to the time required for a volume of liquid to enter (fill up) or exit (empty) a vessel.	Student provides keywords or descriptions unrelated to those in the "Correct responses" column, e.g., the rate at which something flows.
Which parameters affect flow rate?	Student provides keywords pertaining to the size and shape of the orifice (nozzle), the amount of liquid in the container, and additional forces used to push or pull the liquid out, such as a pump.	Student lists parameters that have no relationship with the flow rate, e.g., material of the nozzle or the setup.
Give a physical example of where regulating flow rate is important and how it is regulated in practice.	Student provides keywords pertaining to the movement of liquid, e.g., in a hose, a dam, a shower head, a river etc. The student must give examples of how flow rate is regulated in order to receive full credit, such as regulating flow rate is important when taking shower, the flow rate is regulated by the shower head and faucet.	Student provides keywords, descriptions, or examples unrelated to those in the "Correct responses" column.

Table 3: Rubric for grading students' responses to the pre- and post-lesson content questions.

Contiunes

Content questions	Correct responses	Incorrect response
	Measurements & Accuracy	
Order the numbers from smallest to largest.	Student orders given numbers in increasing order.	Student orders given numbers in incorrect order, or leaves one or more numbers out.
Order the numbers from largest to smallest.	Student orders given numbers in decreasing order.	Student orders given numbers in incorrect order, or leaves one or more numbers out.
Using the ruler measure the height of an object in inches.	Student measures the object accurately and gives its length approximated to the nearest half-inch.	Student measures the length of the object incorrectly with the reported value being off by more than an inch.
What is the difference in height between the tallest and shortest objects?	Student determines heights of given objects to the nearest hundreds and subtracts them to find their difference to the nearest hundreds.	Student provides a difference in height of objects that deviates more than a hundred from the correct answer.
	Pi - What is it?	
Simplify the ratio of circumference to area.	Student correctly write the ratio in terms of radius r and constant π and simplifies it to provide the final expression in terms of radius r.	Student incorrectly writes the ratio so that the simplified expression is incorrect, or incorrectly simplifies the expression, or writes numbers instead of an expression.
How many digits does number π have?	Student states that either the number is irrational or that the digits after the decimal go on forever and never end, etc.	Student gives a finite number of digits, such as three digits as in "3.14", or states that π has one hundred digits, etc.
Calculate the area of the circle.	Student calculates the area correctly with an answer given exactly in terms of π or numerically approximated.	Student provides an answer that deviates greatly from the correct answer, especially by a factor, e.g., a multiple of 10.
What is an irrational number?	Student picks a number that cannot be turned into a fraction or ratio; states that an irrational number is made up of a non-terminating/never-ending decimal, e.g., π.	Student provides an answer unrelated to those in the "Correct responses" column, refers to a number that is not irrational, e.g., –0.3.
	Means, Modes and Medians	
Calculate the mean.	Student correctly calculates the mean of a given set of numbers using a calculator, or gives answer in fractional format.	Student gives an answer that differs from actual numerical mean and performs calculation incorrectly.
Calculate the median.	Student correctly states or calculates the median of a given set of numbers.	Student provides an incorrect value of the median of a given set of numbers.
Calculate the mode	Student provides the correct value of the mode of a given set of numbers.	Student provides an incorrect value of the mode of a given set of numbers.
Solve a word problem with known average and missing data.	Student shows understanding of the problem, provides proper formula for finding the average, assigns a variable value to a unknown data in the set of values, and correctly solves for that unknown.	Student does not show an understanding of how to approach the problem.

Table 3: Continued

consisting of a total of 52 students, and two 10th grade high school science integration classes consisting of a total of 44 students. The math activities outlined above were assessed in three 2nd grade elementary school science and robotics classes consisting of a total of 41 students, one 6th and one 7th grade middle school technology classes consisting of a total of 45 students, and three 9th grade high school algebra classes consisting of a total of 44 students. The activities were conducted in the classrooms where (1) students had limited prior knowledge of the subject matter facilitated by the LEGO Mindstorms setup or (2) teachers believed that the activity would serve as a beneficial supplementary instruction to the previously taught material. During the lesson, GK-12 Fellows and teachers provided timely instruction on the material needed for the students to understand the LEGO Mindstorms-based experiment and to be able to solve the supporting questions provided in the lab worksheet. For this study, each lesson with its corresponding pre- and post-assessment was conducted by employing two consecutive class sessions, wherein the assessments were conducted in two 20 minute periods before and after the 45 minute classroom activity.

Students' responses to content questions were graded following the grading rubric of Table 3 and illustrative examples of students' graded works are available on our website for review. The bar chart representation of assessment results in Figures 7(a), (c), (e) and 8(a), (c), (e) show the percentage of students who responded correctly to pre- and post-activity content questions of science and math lessons, respectively. The assessment results given in Figures 7(b), (d), (f) and 8(b), (d), (f) show the percentage of students' preferences to teaching methods before and after conducting the science and math activities, respectively. Figures 7(a), (c), (e) and 8(a), (c), (e) show that a strong transference of the lessons' underlying concepts occurred during the LEGO Mindstorms-based science and math lessons, respectively. Note that the overall average increase in content question scores for the science and math based lessons was 47% and 25%, respectively. As evidenced by a dependent *t*-test [33] for paired samples and the McNemar's test [33] on paired proportions (Table 4) the improvement in the students' knowledge on post-lesson assessment surveys was statistically significant. The tests were performed on the students' average scores on content questions on the pre- and post-lesson assessment surveys.

Figure 8(e) illustrates a large improvement in students' understanding of the concept of mode in the Means, Modes, and Medians lesson with correct responses improving from 89% to 100%. This gain in students' learning can be attributed to the ease of data collection facilitated through the use of LEGO Mindstorms ultrasonic sensor. This interaction with real data allowed students to couple mathematical concepts taught in the lesson with authentic use of collected numbers, as done by engineers and scientists [34]. By extension this lesson was also helpful for students to learn the concept of frequency and multi modal data. The class average scores were high for other content questions during pre-evaluations for the lesson. This can be attributed to the fact that the

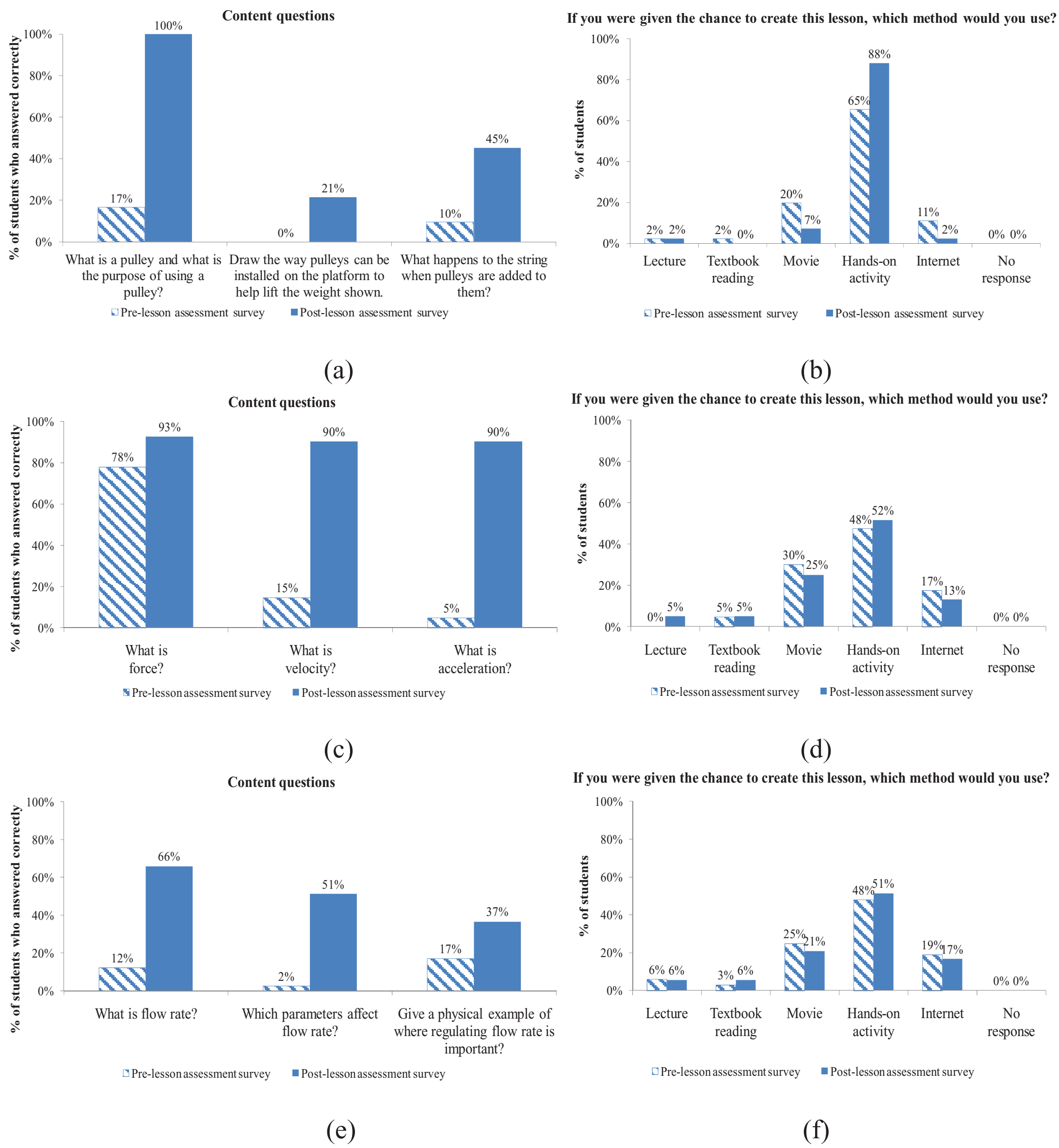


Figure 7. Students' response to pre- and post-lesson content questions assessment for (a) The Mechanical Advantage; (c) Acceleration due to Gravity; (e) Fluid Flow Rate activity and students' response to pre-and post-lesson evaluation Question 2 for (b) The Mechanical Advantage; (d) Acceleration due to Gravity; and (f) Fluid Flow Rate activity.

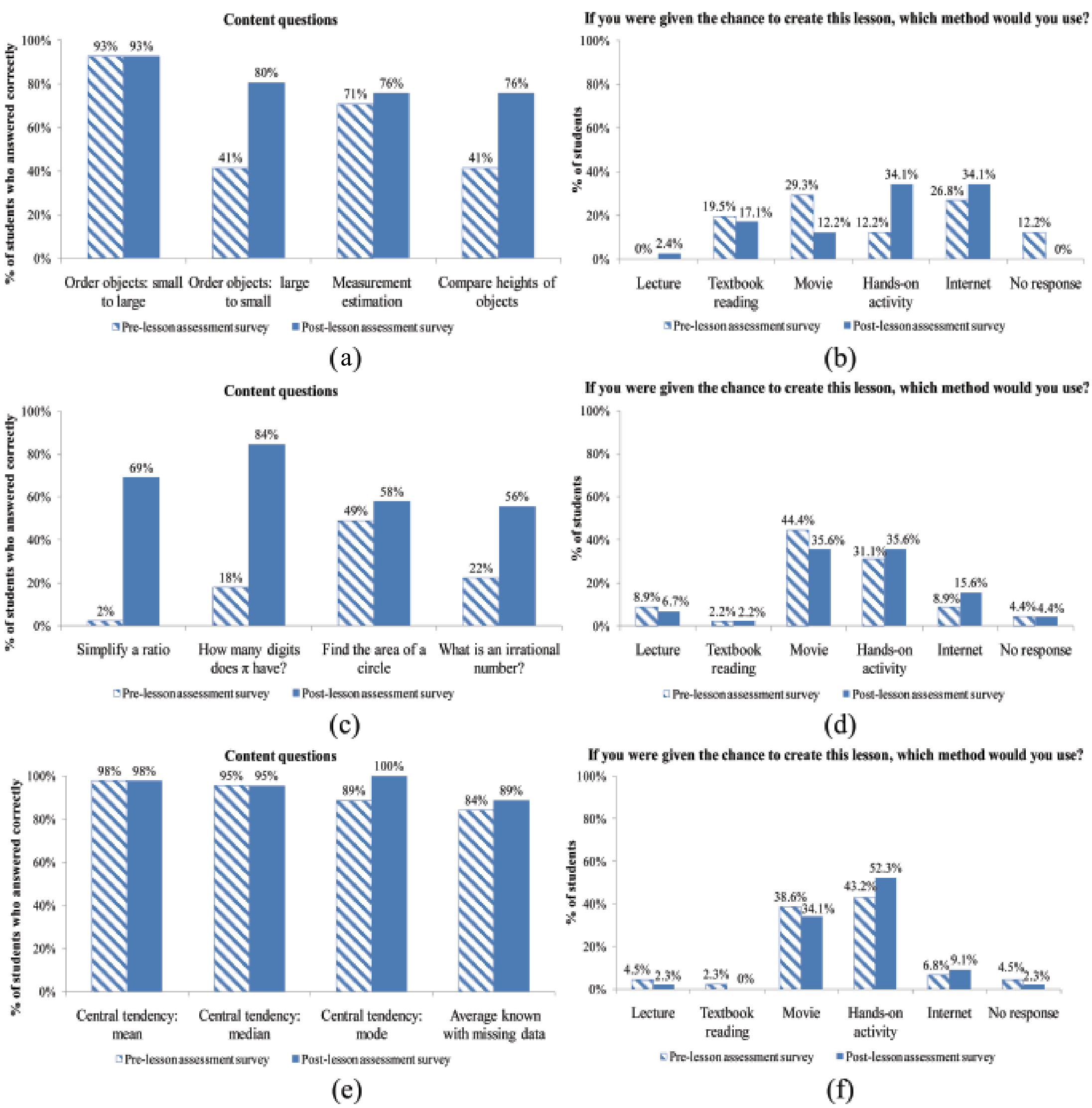


Figure 8. Students' response to pre- and post-lesson content questions assessment for (a) Measurements & Accuracy; (c) Pi–What is it?; (e) Means, Modes, and Medians activity and students' response to pre-and post-lesson evaluation Question 2 for (b) Measurements & Accuracy; (d) Pi–What is it?; and (f) Means, Modes, and Medians activity.

material was covered prior to the lesson and the activity served as a review for the Regents exam. The improvement on these concept questions was low but still significant as shown in Table 4. Similarly, Figure 8(a) illustrates a large improvement in students' understanding of the concept of

Activity	n	Class content questions score statistics: Pre-lesson (%) Avg.	Pre-lesson (%) St. dev.	Post-lesson (%) Avg.	Post-lesson (%) St. dev.	Significance Level: t-test	McNemar's test
The Mechanical Advantage	42	9	18	52	28	< 0.001	< 0.001
Acceleration due to Gravity	41	33	20	91	26	< 0.001	< 0.025
Fluid Flow Rate	41	11	19	51	30	< 0.001	< 0.001
Measurements & Accuracy	41	62	25	81	26	< 0.001	< 0.01
Pi – What is it?	45	23	21	76	30	< 0.001	< 0.01
Means, Modes, and Medians	44	91	17	95	10	< 0.05	< 0.1

Table 4: Results of a dependent t-test for paired samples and McNemar's test on paired proportions for the LEGO Mindstorms-based science and math activities. Here n is the number of student participants in the corresponding activity.

descending order in the *Measurements & Accuracy* lesson with correct responses improving from 41% to 80%. We believe that the combination of traditional instruction, students' interaction with real data, and the presence of a student-friendly robot helped students to retain the knowledge of ordering numbers.

Further analysis of Figures 7(b), (d), (f) and Figures 8(b), (d), (f) shows a consistent increase (pre- versus post-lesson) for hands-on activities as a preferred method for teaching across all lessons. The post-lesson responses reported on all three school levels to the evaluation Question 1 had over 88% and 73% of the participating students displaying a positive attitude towards science and math, respectively. Moreover, the post-lesson responses reported on all three school levels to the evaluation Question 3 had over 66% and 80% of the participating students agreeing that robotic devices can be helpful for data collection in science and math, respectively. The "like" responses to Questions 4 and 5 regarding the robotic device and the lesson, accounted for more than 60% of all the responses among the three school levels for both science and math. The positive responses for Question 6 show that over 70% of the students rated their science lessons as at least "liked" and over 68% of the students rated their math lessons as at least "liked." In response to Question 7, regarding the ease of collecting data with the robot, more than 60% of the students reported that using robotics made both science and math lessons easier. Illustrative descriptive answers to Questions 1, 4, and 5 are provided in Table 5.

The observations on student engagement from the GK-12 Fellows who facilitated the lessons are generally positive for both science and math lessons. Students were reported to be eager to

Activity	Survey question	Response category	Descriptive answers
The Mechanical Advantage	What did you like or dislike about the lesson?	Disliked	"I didn't understand some of the terms used."
Acceleration due to Gravity	What did you like or dislike about the robotic device?	Liked	"I liked how it connected with Bluetooth."
Fluid Flow Rate	What gets you excited about science?	Positive	"Realization of a problem that I always wondered about."
Measurements & Accuracy	What did you like or dislike about the robotic device?	Liked	"It could draw and move."
Pi–What is it?	What gets you excited about math?	Positive	"Using it in engineering."
Means, Modes, and Medians	What did you like or dislike about the lesson?	Disliked	"I dislike robots."

Table 5: Illustrative answers to pre- and post-lesson assessment survey questions for LEGO Mindstorms-based science and math activities.

participate in the lesson and actively encourage other classmates to join. They attentively listened to the lesson descriptions and completed the tasks assigned to them. As all activities were conducted using small groups, informed discussions often emerged where students tried to predict the behavior of the robot or debated conflicting observations on the experimental apparatuses. Students, without former experiences with LEGO Mindstorms, were able to quickly learn to operate the experimental devices and teach it to other students. GK-12 Fellows also reported that some students were uninterested in completing the pre- and post-evaluation surveys with similar questions.

REFLECTIONS, SUSTAINABILITY, AND CONCLUSIONS

The LEGO Mindstorms-based experiments were used to reinforce traditional classroom instruction of New York State mandated learning standards, typically during two consecutive 45 minute class sessions. The lessons can be adapted to support inquiry-based scientific exploration, depending on available time and students' skill level. For example, in *The Mechanical Advantage* lesson students can be engaged in a discussion of the usage of pulleys in everyday life. Similarly, in the *Pi-What is it?* lesson, the program can be adjusted for circles with larger diameters, thus allowing students to discover that π is a constant for all circles. The lessons' descriptions available on our website provide supplemental enrichment content to promote inquiry.

Even as numerous factors [35] are involved in determining whether a lesson is successfully communicated to students, the survey data reveals that students are intrigued by the use of LEGO Mindstorms in the science and math classroom setting. This suggests that students are inherently inquisitive in dealing with science and math topics and are interested in using their senses to learn about the subject in an explorative manner [36–37]. The LEGO Mindstorms-based lessons facilitated students' preferred methods of learning as it fostered their creativity while simultaneously establishing boundaries and structure in accordance with the learning goals of the lesson. The evaluation surveys gauged students' prior experiences with robotics and their beliefs about the usefulness of robotics as a tool for scientific inquiry and data acquisition. Moreover as students were more predisposed to lessons with a hands-on approach, the LEGO Mindstorms-based activities provided the additional effect of keeping students actively engaged throughout the lessons.

Interestingly, students participating in the math based lessons preferred other modes of learning equally and in some cases more than hands-on activities, as depicted in Figures 8(b), (d), (f), even though their attitudes towards the lesson and the robotics device were quite similar to that of the students in science classes. As depicted in Figures 7(b), (d), (f) and 8(b), (d), (f), the difference in learning preferences for students involved in LEGO Mindstorms-based science versus math activities may stem from the students' prior classroom experiences in the subject being taught. Science subjects rely on the interpretation of experimental data for explanations about the observed phenomena. Students readily expect to follow-up or precede a discussion of science topics with some experimentation to provide evidence that supports or disproves a claim; hence a hands-on activity facilitates this purpose. In math classes, such evidenced-based inquiries of the facts are often limited to analogous statements and portrayals. As such, students (and teachers) in math classes may be pre-conditioned to using other learning mechanisms in lieu of hands-on activities.

From this study, two general principles for using LEGO Mindstorms, or similar robotic or experimental devices, in the classroom became apparent. First, a sufficient number of units must be made available to keep the ratio of number of students to the number of LEGO devices relatively low (e.g., 3 or lower). This ensures that all students remain engaged in the task at hand and can follow the structured and explorative components of the hands-on lesson, thus further reinforcing the goals of the lesson. Second, integration of technology such as LEGO Mindstorms in the classroom presupposes that the students possess a fundamental understanding of how the device functions so that they can fully utilize its capabilities. These two principles were observed in this study through (1) the availability of sufficient number of LEGO Mindstorms kits in the participating schools and (2) the collaboration between teachers and GK-12 Fellows to ensure effective delivery of the lesson. Moreover, since the lessons outlined in this study were constrained to being delivered within in a single class period of approximately 45 minutes with an additional 40 minutes allocated for pre- and post-assessment, the programming and design component was eliminated from all lessons to ensure that all students had an equal starting point for participation in the lesson. Moreover, students were not permitted to change or modify the design or program to prevent the apparatus from being compromised and reporting inaccurate data.

To ensure the sustainability of the use of LEGO Mindstorms in the classroom, project teachers have been provided with a foundation of robotics through participation in NYU-Poly conducted workshops. The activities introduced in this paper were conducted at schools that have already been participating in FLL competitions, but did not previously use LEGO Mindstorms in a classroom setting to teach science and math. Therefore, we believe that the activities are sustainable in the participating schools without the continuing presence of a graduate Fellow. Moreover, we offer a step-by-step construction guide and Mindstorms programs (available here) to assist teachers who possess experience in LEGO Mindstorms or have participated in FLL competitions in adopting these lessons.

For teachers unfamiliar with LEGO Mindstorms, NYU-Poly offers periodic workshops. These workshops are open to teachers at all levels of expertise and are conducted by faculty and graduate students for introducing teachers to hands-on science and math activities using LEGO Mindstorms kit. As we conduct additional workshops and survey the workshop attendees, in a future paper, we will report on teachers' workshop experience and their successes or difficulties in integrating workshop activities in the classroom.

To conclude, we recommend several directions for future work. First, the improvement in students' responses to content questions provides an evidence of the effectiveness of LEGO Mindstorms-based experiments in teaching and learning of K-12 science and math subjects. A further study is necessary to establish whether students achieve long-term, sustainable learning gains through engagement with LEGO Mindstorms-based science and math lessons. Such a study requires engaging a cohort of students to conduct multiple LEGO Mindstorms-based science and math experiments throughout an academic year, which was not feasible in the present study due to logistical constraints. Second, as indicated in Figure 8(a) and (e), there were some instances where students' performance did not change between the pre- and post- lesson assessment surveys, suggesting that consideration must be made for the adequate use of LEGO Mindstorms with respect to specific subject contexts. Finally, even though the pre- and post-lesson assessment survey results of our study indicate that the use of LEGO Mindstorms in science and math classrooms was generally received positively by the participating students, it would be informative to conduct a study where identical lessons are taught using conventional, didactic methods and then with the approach outlined in this paper.

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