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Connecting Cognitive Domains of Bloom's Taxonomy and Robotics to Promote Learning in K-12 Environment

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Connecting Cognitive Domains of Bloom's Taxonomy and Robotics to Promote Learning in K-12 Environment

1. Introduction

Learning as currently represented in our K-12 educational system doesn't lend itself to effective classroom environments that stimulate the growth of students' cognitive domains. Instead, many current classroom practices rely on rigid theory, disconnected facts, and computational recipes. Such an approach fails to relate to students' everyday experiences in life outside the classroom. Consequently, when classroom instruction fails to connect theory/facts/procedures with students' conceptualization of ideas, it results in a loss of significance, i.e., students can neither recall nor appreciate the significance of their classroom learning. Alternatively, the ability to recall theory/facts/procedures and their significance allows students to apply ideas more effectively and develop higher-order thinking to synthesize new concepts. In Bloom's taxonomy,[1,2] learning in the cognitive domain is categorized from simple to complex behaviors. Specifically, knowledge, comprehension, application, analysis, synthesis, and evaluation are the behaviors that are typically mastered sequentially due to the nature of their increasing difficulty. Bloom's method allows the development and accurate measurement of students' learning progression through each level of behavior. As behavior at each level is learned sequentially, with each new step in the chain building on its predecessor, this approach allows the development of a deeper level of understanding and higher-order thinking. Designing and conducting classroom activities that support the cognitive learning domains of Bloom's taxonomy can allow students to develop their fundamental and higher-order skill sets. Unfortunately, the current educational system exposes students to only some but not all of the core cognitive learning categories of Bloom's taxonomy.

In this paper, three concrete illustrations demonstrate integration of the entire cognitive learning domain with robotics lessons. The robotics-based lessons offer opportunities to reinforce students' existing knowledge and deepen their understanding of the lessons' content while increasing the likelihood of employing and developing students' higher cognitive domains. Moreover, robotics is known to increase students' enthusiasm and motivation for learning new concepts through engaging hands-on, active learning activities. Educational research[3,4] indicates that active engagement in learning is beneficial for student engagement, retention of knowledge, and improving student comprehension. As evidenced through the existing literature,[5,6] use of robotics in K-12 classrooms to teach science, technology, engineering, and math (STEM) disciplines is well documented. However, the effectiveness of the use of robotics to address students' cognitive domains of Bloom's taxonomy remains to be explored. Mindful design of a learning environment centered on Bloom's taxonomy can guide students through the entire cycle of cognitive domains to ensure that all levels of learning are captured. Specifically, through hands-on lessons, students improve their recall ability, apply their existing knowledge, construct new ideas, and formulate their own questions. Moreover, by engaging in group-work, students are afforded opportunities to share their discoveries and explanations with their peers, thus concretizing their understanding of newly learned concepts. We posit that linking robotics-based lessons with Bloom's cognitive domains can allow students to draw connections between diverse STEM concepts, apply their learning to new situations, and control their own learning.

The example lessons address typical educational objectives of K-12 STEM disciplines and strengthen students' ability to learn the subject material. Three lessons, based on LEGO Mindstorms robotics, are used to transcend age groups from elementary school to high school. For example, one lesson uses a mobile robot with an ultrasonic sensor to navigate around obstacles. First, to allow the elementary school students to develop knowledge and the ability to recall it, verbal and visual connections are drawn between the robot's ultrasonic sensor and a bat's echolocation. Second, to develop their comprehension, the students perform experiments to establish how the ultrasonic sensor interacts with various objects in the environment and its effect on measurements. Third, to develop their cognitive domain of application, the students construct a robot that is capable of movement and uses the ultrasonic sensor to interact with its environment. Having addressed the fundamental cognitive learning domains, the robotics lesson is used to address students' higher-order cognitive skills. First, to allow the development of analysis skills, the students conduct an experiment involving the measurement of reaction time and robot behavior when the ultrasonic sensor is set to several different distance thresholds, i.e., sensitivities. Second, to develop their synthesis skills, the students employ the data collected from the previous step and make inferences about rebuilding their robot to optimize its abilities to maneuver around obstacles. Finally, to develop their evaluation skills, the students obtain qualitative data on their newly synthesized robot design to determine the results of their decisions.

The three activities discussed in the following sections have been implemented in the K-12 classrooms of urban, inner-city (Brooklyn, NY) schools with student bodies largely underrepresented in STEM disciplines. Each lesson addresses core concepts in mathematics that are relevant to the corresponding grades in which the lesson is implemented. The paper illustrates how LEGO robotics has been used to promote the learning of the Common Core State Standards (CCSS) in mathematics[7] while stimulating the students to achieve the entire set of Bloom's cognitive domains. The paper also includes classroom assessment of the three activities and recommendations for future work.

2. Objectives and Assessment Methods

Proportions, geometry, unit conversion, graphing, and engineering design topics are represented in the CCSS for mathematics or the International Technology and Engineering Educators Association (ITEEA) *Standards for Technological Literacy*.[8] While many STEM teachers and adults understand the importance of the aforementioned math topics for diverse real-world situations, many K-12 students find them to be abstract in nature. Thus, one objective of the activities presented in this paper is to make these math topics accessible to the students by having them connect these topics with real-world situations through robotics-based activities. Our first lesson on "Engineering Design Principles using Biomimicry and Robotics," has been developed to demonstrate to elementary school students, through an illustrative engineering design problem, practical applications of concepts such as unit conversion and graphing. Our second lesson on "Trigonometry using Robotics" has been developed to demonstrate to middle school students, through an array of real-world measurement problems, practical applications of concepts such as geometry of right angle and isosceles triangles, the triangle identity involving proportions, and the Pythagorean theorem. Finally, our third lesson on "Human-Computer Interactions using Robotics" has been developed to illustrate to high school students, through a rotary optical encoder, practical applications of concepts from trigonometric geometry.

All lessons are developed by graduate "Fellows" (serving under NYU-Poly's NSF-funded GK-12 Fellows project) in collaboration with their partner teachers. Through initial classroom visits, Fellows observed teachers' approach to teaching various math concepts. They collectively agreed with their partner teachers to design and implement lessons to strengthen the students' understanding of previously taught math concepts through robotics- and engineering-based activities that are visual in nature and build on the students' pre-existing knowledge and experiences. The Fellows and teachers collaborated to: identify the topics to address through robotics activities; develop the sequence of classroom activities to support Bloom's cognitive domains; align the lessons with the required curriculum standards; and schedule and implement the teaching, learning, and experimental activities of the lessons. The three lessons have been taught in age-appropriate classrooms, each lesson at a separate school. Each lesson is conducted over two 45-minute class periods. Throughout each activity, the students are tasked to perform various experimental procedures, obtain and record data, analyze and present their findings, etc., which promotes group-work, independence within a group setting, and traditional independent learning. Moreover, within the group setting, the students often engage in inspired, task-relevant conversation, which strengthened their confidence in the answers they obtained.

To establish the effectiveness of the robotics lessons in the students' learning and understanding of various math concepts, pre- and post-lesson assessments are designed and administered. Pre-assessment questions are designed to quantitatively assess the students' retention and understanding of the underlying concepts of the lesson prior to conducting the robotics-based activities. The pre-assessment questions focus on topics that the students should be familiar with through prior lessons that used typical classroom instruction, but may have had trouble understanding or relating to the material. For example, based on the lesson and grade level, the assessment questions deal with the students' ability to understand and create graphs using the data collected in the activity; concepts related to geometry of triangles; or trigonometry. In a similar vein, the post-lesson assessment questions are designed to evaluate the students' understanding and learning through the robotics- and engineering-based activities. The assessment questions center only on the lessons, i.e., no questions extend beyond the scope of the lessons. Each assessment was administered and collected in an appropriate timeframe and graded individually. The first 15 minutes of the first class period were used for the pre-assessment and the last 15 minutes of the second class period were used for the post-assessment. The results of pre- and post-lesson assessments are appropriately compared to establish the impact of robotics-based lessons.

3. Designing Robotics-based Lessons to Address Bloom's Cognitive Domains

3.1. A Lesson on Engineering Design Principles using Biomimicry and Robotics

3.1.1. Knowledge

Biomimicry is the study of nature to emulate how an animal or plant performs a task. This information is then used to solve a real-world problem. Nature has had millions of years to adapt through the means of natural selection and in recent years engineers have increasingly relied upon the time-tested solutions produced by nature to draw inspiration for engineered products, processes, and algorithms. For example, nature has inspired an array of recent engineering designs such as gecko's feet inspiring adhesives,[9] tumbleweed inspiring a futuristic Mars Lander,[10] clinging hooks of plant seeds inspiring fabric fasteners,[11] and evolutionary principles inspiring artificial intelligence algorithms.[12]

Obstacle avoidance is a problem that many land-, air-, and water-based creatures are accustomed to handle and that many man-made autonomous vehicles must address effectively to be widely accepted by the society. The problem of obstacle avoidance can be addressed in a number of ways. Vision is one common way that many living beings utilize to avoid obstacles. In the case of a low-cost, ground-based robot, however, to reduce computational overhead, alternative techniques inspired by nature are often investigated. For example, nature has endowed bats, dolphins, and whales with the remarkable ability of echolocation to determine their distance to various objects through the reflection of high frequency acoustic signals. Bats are nocturnal and consequently work under very low light conditions. By using echolocation, they have the advantage of being able to detect their surroundings even in the dark. Like bats, whales and dolphins also operate in low light conditions due to their inability to follow normal sleep cycles like most mammalian species on land because of their need to consciously breathe. Specifically, dolphins and whales stay underwater for long durations of time and thus they must make the decision on whether or not they can breathe. Consequently, they sleep by turning off one half of their brain and coast for a period of several hours near the surface to fulfill this need. Considering that they are awake or half awake at all times, they need a non-visual method to detect their surroundings. Through echolocation nature has resolved this problem for them.

For a basic understanding of the principle of echolocation employed by a bat, the students are asked to imagine a scenario where they are in a canyon. To determine their distance from the canyon wall, they must yell loudly and wait to hear the echo to return off of the canyon walls. This is the same process that occurs with a bat's echolocation. Bats emit high frequency sounds that travel across an area, bounce off of obstacles, and return to the bat's ears. Half the amount of time it takes for the sound to return to the bat allows for the determination of the distance to the obstacle.

From an engineering perspective, biomimicry-based echolocation can be incorporated into any design by the use of an ultrasonic sensor. This sensor, in a way similar to a bat's echolocation, emits a high frequency sound wave that reflects off of surfaces and returns to the sensor. Knowing the time for round-trip travel and the speed of sound in air, an embedded processor on-board the sensor can calculate the distance to various objects in its range and field of view.

To reinforce their knowledge, in this lesson the students build and operate a LEGO robot. We discuss with the students that although third-party camera sensors are available for the LEGO platform, they are usually more expensive than other LEGO sensors and require advanced programming strategies. Thus, the students come to understand the impracticality of endowing their LEGO robot with a camera to emulate the vision of an animal and realize that their robot is analogous to animals that need to operate in low light to no light condition. This leads to the discussion and agreement that the LEGO robot needs to be instrumented with an ultrasonic sensor to detect the world around it. In a manner similar to echolocation, the ultrasonic sensor provides the LEGO robot's on-board computer necessary information about objects in front it so that the robot can perform appropriate obstacle avoidance maneuvers.

The LEGO NXT brick serves as the on-board microcontroller of the robot and it allows for quick adaptation of an array of devices such as sensors and motors. Moreover, the NXT brick provides an easy to use platform for children of a large age range (9 years and up) due to its emphasis on the use of LEGO components, which are familiar to students of all ages, and automation using the icon-based programming environment of the Mindstorms ISE. Yet, the NXT is a relatively sophisticated piece of hardware that can serve advanced learners with the use of ROBOTC, MATLAB, and several other formal programming languages. Considering this range of capabilities, the NXT microcontroller is well suited for the biomimicry engineering design lesson.

Biomimicry in engineering design is an excellent way to bring across iterative design principles to the classroom setting because the students can easily relate the technological aspect of the ultrasonic sensor to an animal's use of echolocation. Once again, having the students imagine yelling in a canyon and listening for their echo is another way of creating a concrete knowledge foundation suggested by Bloom's instructive method.

3.1.2. Comprehension

To develop their comprehension of echolocation, the students are engaged in performing object detection experiments using the NXT's view commands with an ultrasonic sensor attached as shown in Figure 1. Through this activity, the students can experience how the sensor detects its environment and how the data is displayed. This experimental activity is performed on three objects of students' choice. Many students use objects that are readily available in a classroom environment, e.g., backpacks, notepads, or chair-legs. This exploration with the ultrasonic sensor and the NXT microcontroller allows the students to learn about the accuracy of the sensor with reference to distances, and how the sensor interacts with changes in the environment, e.g., shape of the object. The students also consider the movement of the sensor or that of the objects in the classroom so that the distances being read by the NXT display captures the changes resulting from movement.

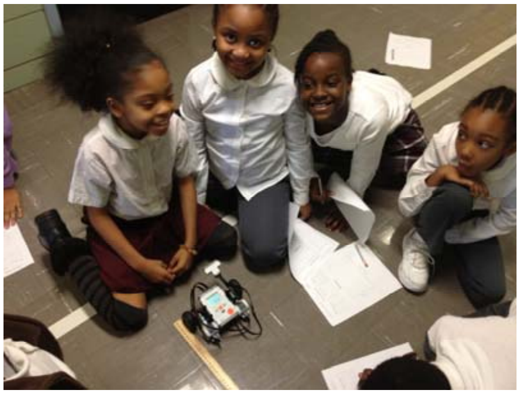


Figure 1: Students using an ultrasonic sensor attached to a LEGO NXT robot

3.1.3. Application

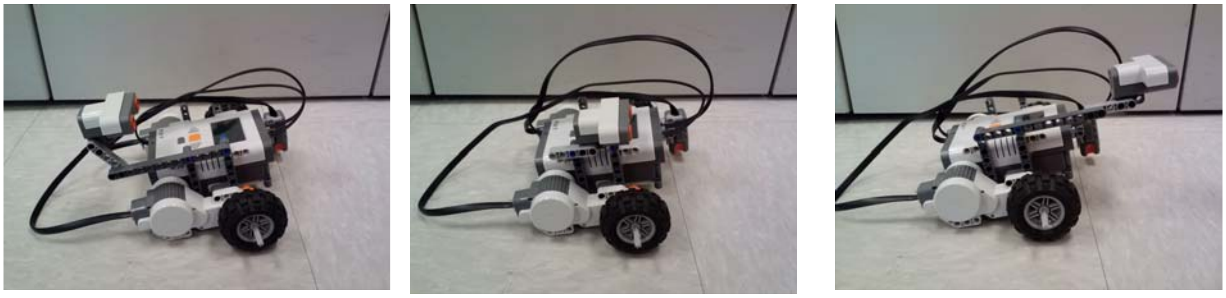
Prior to conducting the application component of the lesson, the design and assembly of a ground-based mobile robot instrumented with an ultrasonic sensor is completed, however the programming of the robot is not. To ensure that the students understand the concepts of how the ultrasonic sensor works, they are guided to upload the "echolocation_program.rbt" program in their Mindstorms NXT IDE so that they can directly inspect and manipulate the threshold values for object detection. This activity allows the students to gain an insight into when the robot will stop moving or react to the obstacle in front of it. Next, the students are split into five groups and are directed to create their own programs that set the threshold of the ultrasonic sensor to 10cm, 25cm, 50cm, 75cm, and 90cm, respectively. After creating the program, the students perform experimental investigations with their robot to assess its performance accuracy in object detection.

3.1.4. Analysis

To develop their analysis skills, the students are asked to place an object at 100cm and then at 200cm distances from their robot. The object detection threshold values of the five robots' ultrasonic sensor are tested simultaneously and the results are shared with the five groups since each group has a different value for their threshold setting. Each group of students then records how long it takes their robot to react to the object. The students go on to compare and contrast the results from each of the groups and draw inferences about how the threshold affected the response time of the robot.

3.1.5. Synthesis

The students employ the data collected from the previous step and make inferences about rebuilding their robot to optimize its abilities to maneuver around obstacles. The student groups are combined to make three groups. These groups are tasked with redesigning the robot for different scenarios, where the ultrasonic sensor is placed on the robot's front, back, or middle as shown in Figure 2. Then the students again perform the aforementioned activity to determine the response time of their robot against objects placed at 100cm and 200cm distances from the robot. They analyze their results within each group and share their answers with all the groups.



(a) (b) (c)

Figure 2: LEGO NXT robots used in the activity with the ultrasonic sensor mounted on the: (a) back, (b) middle, and (c) front of the robot

3.1.6. Evaluation

The students obtain qualitative data on their synthesized robot designs to determine the results of their decisions by re-running the tests from the analysis section. The students are asked how each robot performs in comparison to the others and why. The students are asked to analyze the collected data to examine the importance of sensor placement and to recognize and explain which robot design yields better performance.

3.1.7. Grade Appropriate Adjustments

To make the aforementioned activities grade-level appropriate, several adjustments may be made. The following suggested adjustments increase the difficulty of activities to enforce higher-level concepts that middle and high school students should be able to understand and utilize.

To adjust the analysis activity to incorporate it at the high school level, the students are provided the speed of sound in the air at sea level, which is 340.29 m/s. Using this information, the students determine the theoretical amount of time it takes the robot to react to objects in front of it using simple unit cancellation and conversion. Next, the students perform the experiment and compare their experimental results *vis-à-vis* the theoretical values. This leads to a discussion about the temperature- and altitude-dependence of the speed of sound in air. To scale the lesson to the middle school level, the students are given object detection threshold values in inches, asked to convert them to centimeters, and perform experimental investigations to determine the achieved object detection distance in centimeters. These additional activities emphasize mathematical concepts that are related to grade-appropriate learning standards and tied to practical skills that are useful during the engineering design process.

To adjust the synthesis activity for high school level, the students are allowed complete freedom to place the ultrasonic sensor at any location on the robot based on their consideration, understanding, and experimental examination of various factors that improve the robot's performance. This level of freedom in the design decision permits the students to carefully think through the possible ways of designing a better robot, enforces a direct link to the idea that their decisions impact their results, and allows them to take ownership of their designs.

To adjust the evaluation activity for the high school level, the students are asked to check their experimental results against the previously obtained experimental values and against the theoretical values. A correlation study is performed on how the new results ought to be closer to the theoretical values if their new design is better than the previous one and how it ought to be farther than the first run if their design is worse. This adjustment is conducted to reinforce the value of calculating the theoretical results and then comparing the experimental results *vis-à-vis* the expected theoretical values. Such an approach can also allow the students to uncover sources of experimental errors.

3.2. A Lesson on Trigonometry using Robotics

3.2.1. Knowledge

Trigonometry is the study of triangles and the connection between their angles and sides. Each pair of sides forms an angle less than 180° in a triangle. Since a triangle must be closed, the sum of three angles of a triangle must be equal to 180°. Engineers and construction workers use triangles frequently in the process of designing and constructing buildings. Triangles are used to define or calculate various relations between different parts of a building. Sometimes, however, it is not practical or physically possible to measure the actual distance between objects. Therefore, a variety of electronic instruments are often used to measure distance for hard to reach objects/places. Furthermore, in many everyday life situations and on worksites, it is quite useful to be able to estimate distances. For example, the ancient Egyptians standardized a measurement unit termed *Cubit*, equal to the length of the arm of a royal master from the elbow to the end of the fingers (approximately 18 inches), and used it to build accurate structures such as the pyramids.[13] Through this lesson, the students practice their estimation and measurement skills with the help of trigonometry, which reinforces their knowledge of trigonometry and shows to them the role of trigonometry in real-world problem-solving.

To begin the lesson, we review the following basic concepts of triangles with the students. First, we note that the right angle triangle, which has one angle equal to 90°, is a special form of triangle. Second, we consider different types of triangles based upon the length of the sides. For example, an equilateral triangle is a triangle where all three sides are the same resulting in all angles of the equilateral triangle to be 60° each. Moreover, an isosceles triangle is one whose two sides are the same resulting in two angles of the isosceles triangle being the same. Finally, the scalene triangle contains sides of three different lengths resulting in the three angles of the scalene triangle being different. Throughout this review, suitable illustrations are used to help the students grasp the above concepts. For example, we help the students realize that in any room two adjoining sides (e.g., the floor and a wall or two adjoining walls) form two sides of a right angle triangle making 90° angle between them. As part of this lesson, it is also important to point out to students the names of the sides of a right angle triangle: hypotenuse (longest side), adjacent (base), and opposite (height). For the middle school level students, we explain to them how a protractor works and allow them to practice using it to become more precise in their estimation and measurement of various angles.

3.2.2. Comprehension

To ensure that the students comprehend the lesson, the teacher demonstrates the process of calculating the height of a triangle on the whiteboard in front of the class. This is done in an interactive way that involves the students' participation. First, a right angle isosceles triangle is drawn on the whiteboard. Then, the length of the base of the triangle is given. The students are then asked to identify the type of triangle. Once the students correctly identify it as a 45° right angle triangle, they are asked how they can calculate the height of the triangle. The teacher then guides the students towards the correct answer, i.e., the height of a 45° right angle triangle is same as the length of its base. Multiple types of triangles are demonstrated to ensure that the students grasp the concept.

3.2.3. Application

To test their understanding of the aforementioned concepts, the students are given multiple right angle triangles on a sheet of paper. The length of adjacent side (base) of the triangle is given and the students are asked to estimate the length of the opposite side (height) of the triangle. Some of the triangles have a 45° angle and others do not. Next, to gauge their ability to apply their learning in novel contexts, the students are asked to estimate the height of ceiling in the classroom. To do this activity, middle school students are directed to sit on the ground holding out a protractor at a 45° angle. Then, they move backwards or forwards until they think that the straight edge of the protractor is pointing right at the intersection of the wall and ceiling. Next, the students mark this spot and measure its distance from the wall. Using the analogy of a 45° right angle triangle, the students then estimate the height of the ceiling. These estimates are recorded by the students in their notebook and compared with one another.

3.2.4. Analysis

To develop their analysis skills, a LEGO robot is used to engage the students as shown in Figure 3. The teacher prepares this part of the lesson by placing tape on the floor in the shape of a right angle isosceles triangle. Next, the students are handed the LEGO robot that has been programmed to travel a set distance, equal to the length of the base of the triangle taped on the floor. The students are asked to place the robot at the corner formed by the hypotenuse and the base of the triangle such that it travels along the base of the triangle upon the program execution. When the program terminates, within some experimental tolerance, the robot is found to have reached the corner formed by the triangle's base and height. Next, the students rotate the robot by 90° and run the same program again. Through this experimentation, the students verify in a visual manner that the two sides of a right angle isosceles triangle are equal.

(a)

(b)

Figure 3: A LEGO NXT robot used in the activity: (a) tracing a triangle and (b) increasing student engagement in the lesson

The students use observations from the above step and make inferences about any differences they noticed between the actual height of the triangle and their estimates. The students are led to discuss what other things can be estimated with the trigonometry techniques that they have learned. Their suggested answers include buildings, skyscrapers, bridges, cell-towers, and homes. Finally, we ask the students why using an electronic sensor or math might work better than a yardstick when building a skyscraper. We ask them to imagine engineers trying to measure the height of a skyscraper with a yardstick! We also engage them in discussions about estimating the height of a suspension bridge, estimating the height of a building based on the shadow it casts, etc. Finally, the discussion ends with the consideration of measuring even more distant objects by using more complex geometry or other types of sensors, e.g., the distance from one city to another, distance to the moon or sun, etc.

3.2.5. Synthesis

To develop their ability to perform synthesis activities using their newly acquired knowledge, we ask the students what they would do to estimate the horizontal (ground) distance from the top of one building to another building or a landmark far away, assuming that they knew the height of the building they were on. The students are shown sketches and drawings to illustrate how the same triangles we used in the previous problem can be employed in this new situation. Next, we have the students stand on top of a table or chair and use a LEGO setup with an ultrasonic sensor to estimate how far away an object is in the classroom. Finally, the students compare the actual distance with their estimates.

3.2.6. Evaluation

For the evaluation phase, the students compare the accuracy of their results in subsection 3.2.3 in measuring the height of the ceiling in the classroom. Specifically, while standing flush with a wall, they are directed to use a LEGO setup with an ultrasonic sensor to measure the distance from their shoulder to the ceiling as well as from their shoulder to the ground. By adding these two values, the students obtain the height of the classroom. Next, these values are compared with the prior results obtained in subsection 3.2.3. The teacher also provides the students actual height of the ceiling. Next, we discuss with the students strategies to improve their estimates. Finally, post-assessment questions are used to assess the students' understanding of trigonometric concepts.

3.2.7. Grade Appropriate Adjustments

To make the aforementioned activities grade-level appropriate, the following suggested adjustments decrease (increase) the difficulty of activities to accommodate younger (older) students.

To adjust the knowledge activity, for the elementary school level students, we begin the lesson by considering a square and asking the question: What makes a square a square? Through illustrations, the students come to understand that a square has four sides all of which have same length and the adjoining sides of the square all form 90° angles. Next, we investigate the result of slicing a square diagonally and examine the resulting shape. That is, the students are asked to name the kind of triangle formed. They are led to consider that the resulting triangle has two equal length sides that form a right angle. We explain to the students that for the purposes of this class we will use the length of one side of a right angle triangle to estimate the length of the other (equal-length) side. We have the students practice estimating a 45° angle with their arms. For example, in the application phase, when measuring the height of ceiling in the classroom, the elementary school students move about in the classroom holding out their arm at approximately a 45° angle

To adjust the knowledge activity, for the high school students, we begin the lesson with a review of all trigonometry concepts mentioned above, including the use of a protractor. Next, we explain to the students the basics of sine and cosine functions and how they relate to right angle triangles. Moreover, we ask the students to investigate how the knowledge of the distance of the base of the triangle along with the angle formed with the hypotenuse constitutes sufficient information to calculate the height of the opposite side of the triangle. For example, in the application phase, when measuring the height of ceiling in the classroom, instead of a 45° angle, the students are asked to use a different angle and follow the same procedure as above with a protractor. Finally, the high school students can also be asked to measure the angle formed by the known side of a right angle triangle and its hypotenuse.

3.3. A Lesson on Human-Computer Interactions using Robotics

3.3.1. Knowledge

People interact with computers and electronic devices every day performing many of their daily activities. In a majority of these devices, human actions have to be registered through mechanical devices that are then interpreted by electronic circuits or computers. Common mechanisms to register human actions include buttons, dials, knobs, touch screens, etc. Finally, the interpreted information is fed back by the computer to the human users so that they can understand their interaction with the computer. It is common for many users to operate and interact with a machine, device, or system without knowing or understanding its inner workings, and thus treat it as a "black-box." In fact, in engineering, the terminology black-box is commonly used to refer to a complex machine, device, or system that is used without knowing its internal workings. In this lesson, the students are exposed to the engineering applications of rotary encoders, specifically for human-computer interaction, and they perform activities that help demystify the black-box inside the common computer mice.

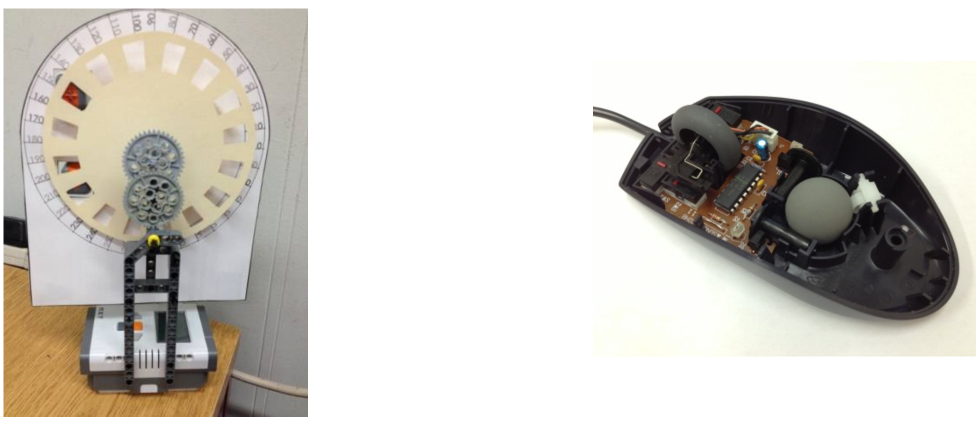
A rotary encoder is an electromechanical device that is used to convert an angular displacement into a digital code. Rotary encoders are used in a wide array of applications and devices such as computer mice, elevators, robotic arms, and stereo docks. Rotary encoders constitute one type of mechanism that is widely exploited in human-computer interaction systems.

On a personal computer, one of the most common forms of human-computer interactions is through a computer mouse. The computer mouse helps users accomplish a great deal of work by allowing them to effortlessly and intuitively move the cursor on a 2D computer display. Surprisingly, the design and operating principle of a computer mouse consisting of two rotary encoders and associated electronic circuitry is very simple. As the computer mouse is moved horizontally left-to-right or back-and-forth, the corresponding encoder's rotary wheel converts the translational motion into rotational motion. Next, the turning motion of each rotary wheel is transformed into translation of the computer cursor in one dimension and the rotation of two wheels produces a planar 2D working area. In this activity, a LEGO robotic mechanism is developed and used to model and illustrate the principle of the rotary encoders using two light sensors. The turning motion of the rotary wheel is translated into a command which changes the value of a variable counter which is displayed on the LCD display of the NXT microcontroller.

For the high school students, the concept of how rotary encoders relate the light sensor output to digital code is rigorously presented through the explanation of 2-bit encoding. Furthermore, a direct application of this concept to computer mouse is considered.

3.3.2. Comprehension

The students observe the application of a rotary encoder through two examples, which reinforce their knowledge, learned through the lesson, by showing concrete illustrations of the working of encoders. The first example consists of a demonstration of a physical model of a rotary encoder built from a LEGO NXT kit, see Figure 4(a). In the demonstration, the designed encoder is marked with angles for each cutout slot on the encoder. The LCD display of the NXT brick shows a variable counter for the angle as the rotary wheel is turned. Thus, the students are able to observe how the turning of the encoder changes the displayed angle. The second example requires the students to disassemble a computer ball mouse, see Figure 4(b), and observe that it consists of two small rotary encoders. The students correctly observe that the two encoders are aligned orthogonally so that the turning of the rotary wheels correlates to a two-dimensional working space. They conclude that the computer ball mouse uses the rotary encoder to determine if the wheel is spinning in one direction or another and the computer reads the transmitted information to incrementally add one pixel along the axis of interest. The movement of the mouse cursor on the computer screen results from the combination of the light passing through the slits on both the turning rotary encoders in the mouse.



(a) (b)

Figure 4: (a) LEGO-based rotary encoder model and (b) Computer mouse

3.3.3. Application

To gain a preliminary understanding of the rotary encoder, the high school students observe its application in the computer ball mouse. The students disassemble a computer ball mouse to look inside and see the electro-mechanical design. The students describe the components and identify the rotary encoder by drawing what they see. Through this action, the students can observe the role of various electro-mechanical components in the computer mouse black-box. The students then connect this mouse to a laptop or desktop computer to observe the mouse cursor. Using this dissected computer mouse, see Figure 5, the students move the rotary encoder and examine the changes to the motion of the mouse cursor on screen using a pixel ruler. The students measure the pixel change according to the distance the computer mouse has travelled. In this experiment, the students learn that the rotation of the ball will turn the encoder wheel. This rotation is translated to a pixel change in the vertical or horizontal direction on the computer screen. In addition, the students identify which encoder shaft controls which direction on the computer screen. By graphing their findings, the students find that the translation is linear.

(a) (b)

Figure 5: (a) A typical student drawing identifying a rotary encoder in (b) a dissected computer mouse

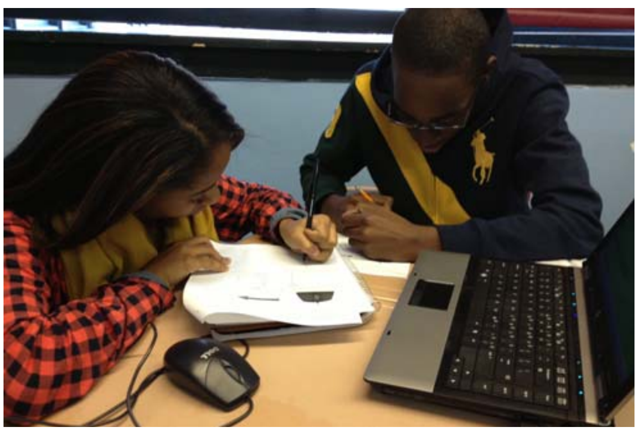
During this activity, the students also use a LEGO mechanism designed to model an encoder, see Figure 4(a). They are called upon in groups to interact with the LEGO mechanism. The LEGO-based model rotary encoder appears like a Ferris wheel but is in fact an enlarged version of the mechanism observed by the students in the computer mouse dissection activity. The students are assigned up to three angles to use on the rotary encoder. First, the students predict how much they need to turn the wheel to reach the desired angle. Next, they turn the encoder wheel and record both the desired angle and the angle displayed on the LCD display of the NXT brick. They repeat the activity and measurements for the three assigned angles and write down their observations and explanations for the discrepancies in the obtained results.

The high school students are tasked with using the mouse to roll a certain length on a paper and then measure the amount of pixels travelled on the computer. Next, the students determine that the length measured on the paper correlates with the virtual movement on the computer. The students compare their results with other groups' pixel/length travel ratio, discuss on similarities and differences, and brainstorm possible explanations.

3.3.4. Analysis

To sharpen their analysis skills, and according to their grade level, the students are engaged in practicing their math skills on the collected quantitative data and qualitative explanations. This is done through the observation of drawings, comparison of the angles data collected using the LEGO-based encoder model, and graphing the computer mouse data. Various comparisons are identified, recorded, or plotted if students are familiar with graphing procedures.

The high school students perform both the computer mouse drawing activity and the data collection experiment using the LEGO-based encoder model (Figure 6). After obtaining the pixel and length measurements, the students plot their results with "length on paper" on the *x*-axis and "pixel length" on the *y*-axis. Using a ruler, the students draw a linear curve fit and optionally calculate the slope of the curve. The students brainstorm the meaning of the shape of the slope in the context of the computer mouse. For the LEGO-based model rotary encoder setup, the high school students move the wheel to marked-positions 0, 45, 90, 135, 180, 270, and 360 degrees. After the experiment is performed, the students examine the error in the experimental data, i.e., the actual angular displacement versus the angle displayed on the LCD screen of the NXT brick. The students then comment in a class discussion on the possible sources of the error and the amount of error that may be allowed in a computer mouse without sacrificing its performance.


(a)

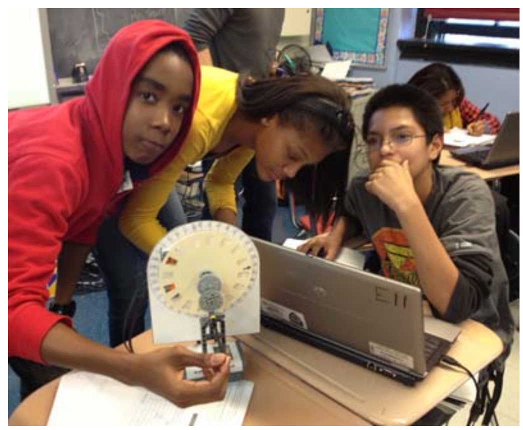

(b)

Figure 6: (a) Students performing the pixel data collection and (b) LEGO NXT data collection

3.3.5. Synthesis

The students utilize their knowledge of rotary encoders to brainstorm how other everyday engineering systems operate. The students discuss elevators that transport people from one floor to another accurately with safe operating speed. In an elevator, a motor turns a cable to bring people to different floors. It is rare that an elevator would reach halfway between floors and open its doors, or even open if it is half a foot above the floor level. The students brainstorm together to explain how this is possible based on their understanding of the rotary encoder. The students are then asked to design an elevator door that makes use of rotary encoders.

3.3.6. Evaluation

The students discuss their findings from dissecting the computer mouse, location of the encoder, observation on how the movement of the encoder changes the mouse cursor; and movement of the LEGO-based rotary encoder model and collected results on angles. They comment on whether their experiments match their predicted result and the causes of the differences/similarities. Finally, the students are tested with questions on the topics of rotary encoders, human-computer interaction, and on angles. They are also surveyed on their comfort level concerning the topics covered in the lesson. Both quantitative and qualitative questions are used to measure their growth and the impact of the activity.

3.3.7. Grade Appropriate Adjustments

To adjust the knowledge activity, for the middle school students, the investigation of how an encoder works naturally leads us to address the topic of angles. Finally, for the elementary school students, the lesson focuses on developing the idea of discovering and understanding a black-box. The following two questions are considered: have the students ever seen what is inside a computer mouse and do they know what happens when a rotary encoder turns?

To adjust the application activity, the elementary school students create drawings with a pencil attached to a mouse and are questioned as to why they thought the drawings appeared similar to the images on the computer. The explanation is presented to the students using an enlarged rotary encoder modeled using the NXT kit to illustrate how it creates images.

To adjust the analysis activity, the middle school students dissect the computer mouse and illustrate the rotary encoder component. The middle school students experiment with fewer angles on the NXT and identify the difference in the desired and displayed angle. The elementary school students are shown the inner working of a single computer mouse. For the drawing activity, the elementary school students explain why their drawings on paper and the ones on the screen are similar but not exactly the same. In writing, the students compare the similarities and differences of the drawings with respect to shape, scale, and roughness.

4. Lesson Assessments

In the following subsections, statistical hypothesis tests and bar charts are used to compile and analyze assessment results for each of the three lessons described in Section 3. To examine whether the students' performance from pre- to post-tests yields statistically significant gains, a dependent *t*-test for paired samples is used for individual content questions and for each student's average scores on content questions. For completeness, pre- and post-test class averages for each content question are provided as bar charts.

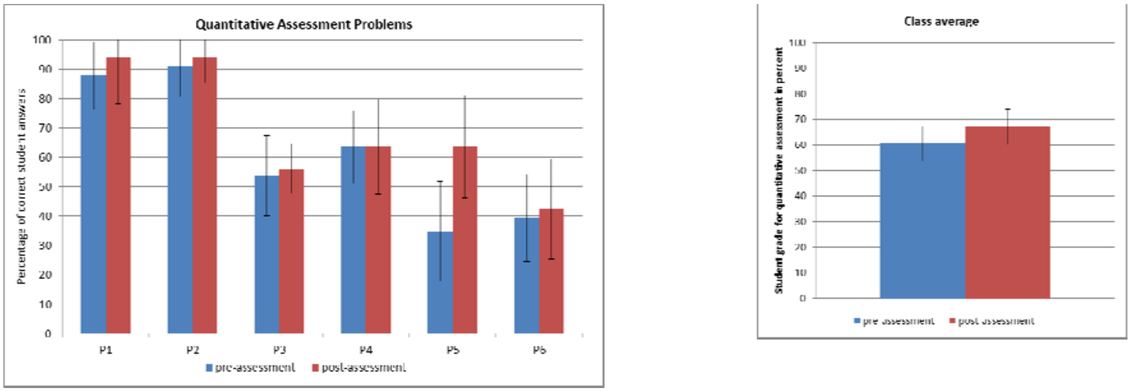
4.1. A Lesson on Engineering Design Principles using Biomimicry and Robotics

The echolocation in robotics activity has been implemented in a Brooklyn elementary school classroom of 33 students. At the beginning of the lesson, the students were asked to complete a pre-assessment and a short overview of the lessons content was presented. Next, the students were divided into three groups and directed to attach an ultrasonic sensor to their robot. The students conducted experiments to determine the effects of changing the placement of the sensor on the robot and the object detection threshold value of the sensor. Following the experiments, the students plotted their experimental results, which allowed them to practice graphing skills and interpret their findings. Finally, the students were administered a post-lesson assessment to complete. The lesson and its associated activities supported the standards identified in Table 1. The assessment questions are provided in Appendix A, Table A.1.

Table 1: Elementary School Standards

Topic	Content
State Standards (Math: Grade 6)	Standard 6.PS.3: Interpret information correctly, identify the problem, and generate possible strategies and solutions
CCSS (Math: Grade 5)	Standard 5.G: Graph points on a coordinate plane to solve real-world and mathematical problems.
ITEEA Standards (Grades K-12)	Standard 9: Develop an understanding of engineering design.

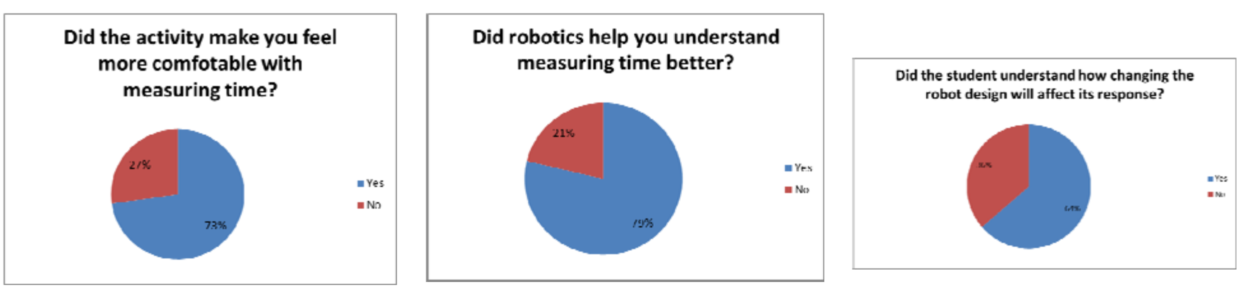
The results of pre- and post-lesson assessments in Figure 7(a) indicate that the lesson and its activities positively impacted the students' knowledge of ultrasonic sensors, graphing, and measuring time. Note that as the level of difficulty increases from Problem 1 (P1) through P6 (to support Bloom's cognitive domains), average class scores decline. While the students' responses to P1—P4 and P6 show only minimal improvement in class averages, their responses to P5 show a large improvement in the class average from pre- to post-lesson assessment. On P4, many students found it hard to relate to the cause and effect relationship, which may be explained by their young age. The larger gains on P5 can be explained by the fact that a part of the activity required the students to graph the data they had obtained in their experiments with robots. Taken as a whole, in Figure 7(b), the pre- and post-lesson assessments show a small increase in the class average following the robotics activities. The small difference between the pre- and post-assessment averages can be due to several factors. First, the lesson and its associated assessment are possibly more complex than the Fellow and his partner teacher originally anticipated. While the class averages on P1 and P2 were high to begin with, P3 and P6 showed only marginal improvement and P4 showed no improvement. Finally, the qualitative survey questions (see below) may have added to the length of the assessment. Overall, it is suggested that at the elementary school level pre- and post-lesson assessments be short, simple, and direct.



(a) (b)

Figure 7: Performance of class before and after activity: (a) class average for individual questions and (b) class average for the entire assessment

In addition to the six content questions, the post-lesson assessment sought the students' responses to three qualitative questions. As shown in Figure 8, a large percentage of students became comfortable in measuring time and indicated that the robotics activity played a role in that increase of comfort. Finally, over half of the students were able to comprehend a key point of the lesson, namely that changing the location of the ultrasonic sensor would have an impact on how the robot would sense its environment. This illustrates the students' transition from a lower to a higher cognitive domain through their ability to apply what they learned and predict what would happen to the robot's reaction time.



(a) (b) (c)

Figure 8: Qualitative results for the post-assessment survey

A dependent *t*-test for paired samples was performed to evaluate the differences in the students' responses on the pre- and post-lesson assessment surveys for each individual content question and their average scores. The results of *t*-tests indicated that the null hypothesis at 5% significance level cannot be rejected, that is, no significant statistical difference existed between the students' scores on the pre- and post-lesson assessments for each individual question and their average scores. The only exception to this was P5, for which we obtained a *t*-value of 3.37

that allows us to reject the null hypothesis that there was no change in the students' performance using a 0.2% significance level or better.

Even as the students demonstrated promising results on the comprehension of the lesson's main focus, they were not always able to formulate correct answers on the post-lesson assessment. As previously mentioned, in both the pre- and post-lesson assessments, the students performed well on the conceptually simple first two questions, thus reflecting their ability within the lower cognitive domains. P3, P4, and P6 asked the students to use what they had learned to predict what would happen, requiring the use of a higher cognitive domain. This proved to be more challenging to the elementary school students, as reflected by the data in Figure 7. Nonetheless, the students exhibited marginal gains even on these problems, and on P5, from the pre- to post-lesson assessment, thus showing improvement in their knowledge within the higher domain.

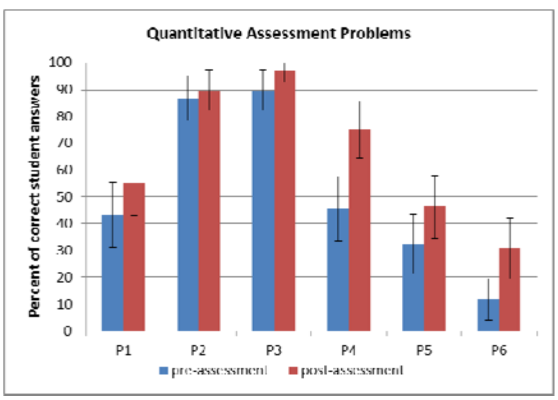
4.2. A Lesson on Trigonometry using Robotics

The trigonometry using robotics activity has been implemented in several classrooms of a Brooklyn middle school with 68 sixth and eighth grade students. At the beginning of the lesson, the students were asked to individually complete a pre-assessment and a short overview of the lessons content was presented. Next, the students were divided into groups of three to four students to perform the lesson's hands-on activities. The students conducted experiments to (1) determine the height of the ceiling in the classroom using the protractor activity and the ultrasonic sensor activity and (2) verify that the base and height of a right angle isosceles triangle are equal using the robotics activity. Following each activity, the students recorded their experimental data and analyzed it to compare and interpret their findings. Finally, the students were administered a post-lesson assessment to complete. The lesson and its associated activities supported geometric concepts and algebraic proportions through the use of right angle and isosceles triangles, the triangle identity involving proportions, and the Pythagorean theorem, which are all part of the CCSS for middle school as shown in Table 2. The assessment questions are provided in Appendix A, Table A.2.

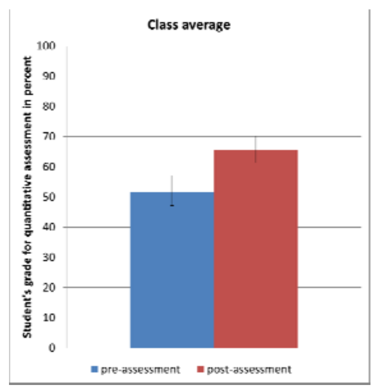
The results of pre- and post-lesson assessments in Figure 9(a) indicate that the lesson and its activities allowed the students to demonstrate a better understanding of triangular geometry. They showed an improved ability to differentiate between a square and a triangle, name an attribute of triangle, and identify a type of triangle, among other tasks. Similar to the case of elementary school students, as the level of difficulty increases from P1 through P6 (to support Bloom's cognitive domains), average class scores decline. Comparing pre- to post-lesson assessment of class averages for individual questions, the students' responses to P1—P3 and P5 show marginal improvements while their responses to P4 and P6 show relatively larger improvements. Note that the class averages on P2 and P3 were high to begin with. Moreover, the students' responses to P4—P6 in pre-assessment illustrate their low comfort level with the examined concepts. The large improvement in the post-assessment data for P4 and P6 indicates that the students greatly developed their abilities through Bloom's higher cognitive domains. Taken as a whole, in Figure 9(b), the pre- and post-lesson assessments show an increase in the class average following the robotics activities.

Table 2: Middle School Standards

Topic	Content
CCSS (Geometry)	Standard 7.G: Draw, construct, and describe geometrical figures and describe the relationships between them.
	Standard 8.G: Understand and apply the Pythagorean theorem.
CCSS (Math: Grade 8)	Standard 3: Students use ideas about distance and angles, how they behave under translations, rotations, reflections, and dilations, and ideas about congruence and similarity to describe and analyze two-dimensional figures and to solve problems.



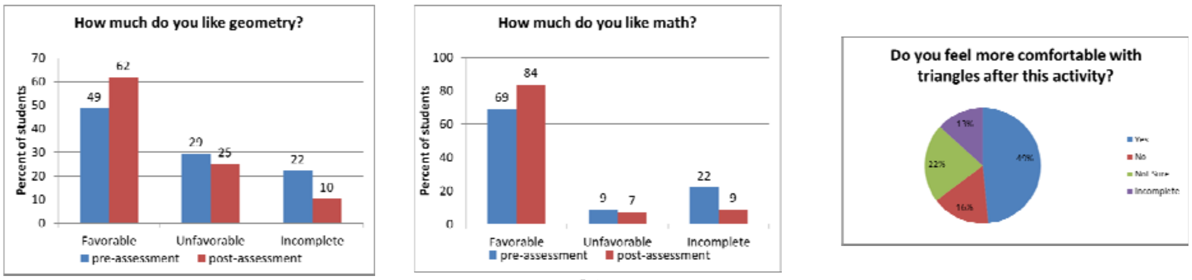
(a)



(b)

Figure 9: Performance of class before and after activity: (a) class average for individual questions and (b) class average for the entire assessment

In addition to the six content questions, the post-lesson assessment sought the students' responses to three qualitative questions pertaining to their comfort levels in the areas of geometry and math. Their answers that corresponded with comfort level (1) "a lot" and "a little" are combined and treated as favorable answers and (2) "not at all" and "don't know" are combined and treated as unfavorable answers. Figure 10(a) shows a 13% increase in students who responded favorably to liking geometry from pre- to post-assessment with a corresponding decline in the unfavorable and incomplete answers. Moreover, Figure 10(b) shows a slight increase in students who like math from pre- to post-assessment and a slight decline in the incomplete answers. Finally, Figure 10(c) indicates that although 16% students answered “no” to being “more comfortable with triangles” after the lesson, the students who answered “yes” or “not sure” formed a majority and consisted of 49% and 22% of students, respectively.



(a) (b) (c)

Figure 10: Qualitative results for the pre- and post-assessment survey

A dependent *t*-test for paired samples was performed to evaluate the differences in the students’ responses on the pre- and post-lesson assessment surveys for each individual content question as well as on their average scores. As seen through Table 3, for P1, P4, P6, and students’ average scores, the results of *t*-tests reject the null hypothesis that there was no change in the students’ performance using a 5% significance level or better, i.e., their performance from pre- to post-test increased significantly and we can state with a confidence level of 95% or higher that the robotics-based activities played a significant role in this gain. However, for P2, P3, and P5, the results of *t*-tests indicate that the null hypothesis at 5% significance level cannot be rejected.

Table 3: Results of a dependent *t*-test for paired samples. Values calculated using students’ responses to each individual content question as well as on students’ average scores, with *n*=68

Item	Mean Difference	Standard Dev.	*t* calculated	*p* Value
P1	11.8	44.1	2.21	< 0.05
P2	2.9	38.5	0.63	Not Sig.
P3	7.4	31.5	1.94	Not Sig.
P4	29.4	49	4.98	< 0.001
P5	14	59.8	1.94	Not Sig.
P6	19.1	43.2	3.67	< 0.001
Aver.	14.1	23.6	4.96	< 0.001

As evidenced through Figure 9(a) and Table 3, the students showed transition from the lower cognitive domain to the higher cognitive domain through the quantitative assessment of P1, P4, and P6. Significant improvement for each of these questions illustrates student gains in the knowledge and comprehension domains. Moreover, the students demonstrated transition to the analysis domain in P4 through their improved ability to identify the features of the triangle they drew in P3. For P2 and P3, no significant increase was seen in student performance as evidenced through Figure 9(a) and Table 3. However, note that the student scores were higher than 86% for P2 and P3 in pre-assessment, indicating that a vast majority of the middle school students understood the material prior to the lesson activity and thus the *t*-test did not yield any significant improvement. Furthermore, during the synthesis component of the lesson, the graduate Fellow appropriately questioned the students about abstracting the concepts taught on triangle geometry and applying it to objects such as skyscrapers. Such an approach allowed the examination of students' ability to connect their earlier learning on right angle triangles to real-world situations. Many students answered remarkably well on how they would utilize the geometry of right angle and isosceles triangles and the triangle identity involving proportions to determine the unknown side of a triangle in a real-world measurement and estimation problem. Moreover, to determine the length of the hypotenuse, they correctly indicated the need for the use of the Pythagorean theorem.

4.3. A Lesson on Human-Computer Interactions using Robotics

The human-computer interaction using robotics activity has been implemented in a Brooklyn high school classroom of 42 ninth grade students. At the beginning of the lesson, the students were asked to individually complete a pre-assessment and a short overview of the lessons content was presented. Next, the students were divided into groups of three to four students to perform various hands-on activities of the lesson. Through the lesson-overview and hands-on activities with the computer mouse and the LEGO rotary encoder, the students learned about angles, rotary encoders, and human-computer interaction. Finally, the students were administered a post-lesson assessment to complete. The lesson, its associated activities, and the assessment worksheets were designed with consideration to the CCSS for mathematics[6] and the Human Computer Interaction Unit.[14] Note that the Human Computer Interaction Unit was already being used by the teacher in the technology curriculum. As seen through Table 4, geometry, angles, measurement, data collection, and graphing are all important topics in high school curriculum. The assessment questions are provided in Appendix A, Table A.3.

The results of pre- and post-lesson assessments in Figure 11(a) indicate that the lesson and its activities allowed the students to demonstrate a better understanding of angles. Comparing pre- to post-lesson assessment of class averages for individual questions, the students' responses to P2—P4 show large improvements, while their responses to P5 show relatively smaller improvement, and finally their responses to P1 show a small decline in correct responses. Taken as a whole, in Figure 11(b), the pre- and post-lesson assessments show a modest increase in the class average following the robotics activities.

Table 4: High School Standards

Topic	Content
CCSS (Geometry)	Standard G-CO: Make formal geometric constructions with a variety of tools and methods
	Standard G-MG: Use geometric shapes, their measures, and their properties to describe objects
Human Computer Interaction Unit	Explore the concepts of computer and computing by investigating computer hardware components and a variety of internet resources

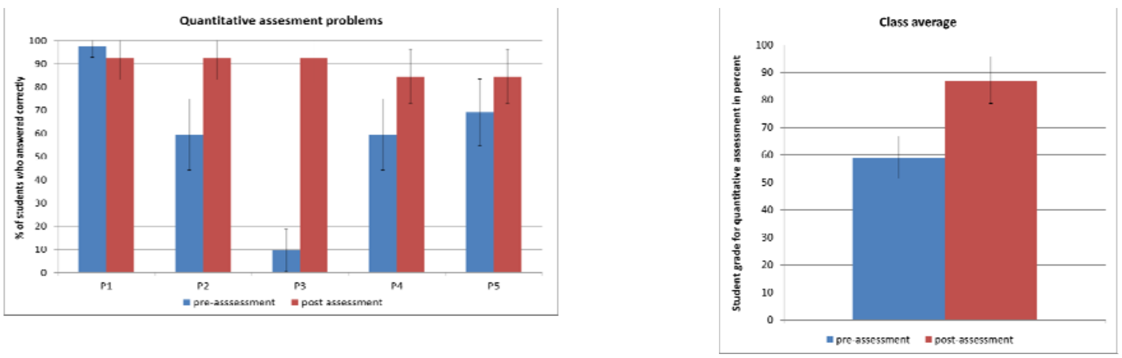
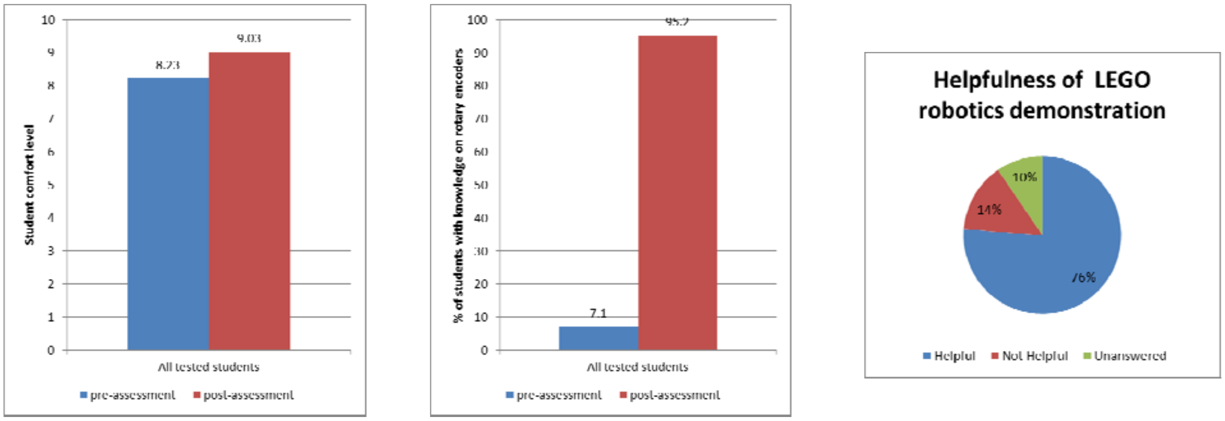


Figure 11: Performance of class before and after activity: (a) class average for individual questions and (b) class average for the entire assessment

In addition to the five content questions, the assessment sought the students' responses to three qualitative questions pertaining to their comfort levels with the topic of angles and their knowledge on rotary encoders. Figure 12(a) shows that the students' comfort level with the topic of angles increased slightly after the activity. Moreover, Figure 12(b) shows that while only a small percentage of students were knowledgeable about rotary encoders prior to the activity, a very large percentage of students became knowledgeable about rotary encoders after the activity. Finally, Figure 12(c) indicates that a large majority of students attributed their increased understanding of the rotary encoder to the LEGO-based encoder activity.

A dependent *t*-test for paired samples was performed to evaluate the differences in the students' responses on the pre- and post-lesson assessment surveys for each individual content question as well as on their average scores. As seen through Table 5, for P2—P4 and students' average scores, the results of *t*-tests reject the null hypothesis that there was no change in the students' performance using a 1% significance level or better, i.e., their performance from pre- to post-test increased significantly and we can state with a confidence level of 99% or higher that the robotics-based activities played a significant role in this gain. However, for P1 and P5, the results of *t*-tests indicate that the null hypothesis at 5% significance level cannot be rejected.



(a) (b) (c)

Figure 12: Qualitative results for the pre- and post-assessment survey

Table 5: Results of a dependent *t*-test for paired samples. Values calculated using students' responses to each individual content question as well as on students' average scores, with *n*=42

Item	Mean Difference	Standard Dev.	*t* calculated	*p* Value
P1	0.071	0.342	1.35	Not Sig.
P2	0.310	0.563	3.57	< 0.001
P3	0.785	0.415	12.26	< 0.0001
P4	0.238	0.532	2.90	< 0.01
P5	0.143	0.566	1.63	Not Sig.
Average	0.281	0.339	5.363	< 0.0001

On pre- and post-tests, content questions were used to assess the lower domains such as knowledge and comprehension. As evidenced through Figure 11 and Table 5, the students performed better on content questions on the post- versus the pre-test. This shows that the lesson was effective in reinforcing the topic of angles and improved the students' performance in the lower cognitive domains. Next, as seen in Figure 5, the students were able to correctly identify and label the encoders after they dissected the computer mouse using their newly acquired knowledge on rotary encoders. Moreover, as they performed the pixel ruler data collection (see Figure 6), the students gradually transitioned to the application and analysis domains. The students used their understanding on the rotation of the rotary encoder to create its relation to the movement of the cursor on the screen and found a linear correlation (see Figure 13). As seen through Figure 12(b), a large majority of students indicated having gained knowledge about rotary encoders.

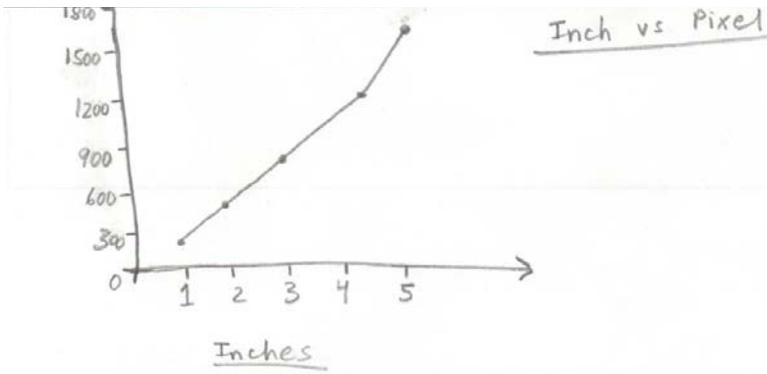
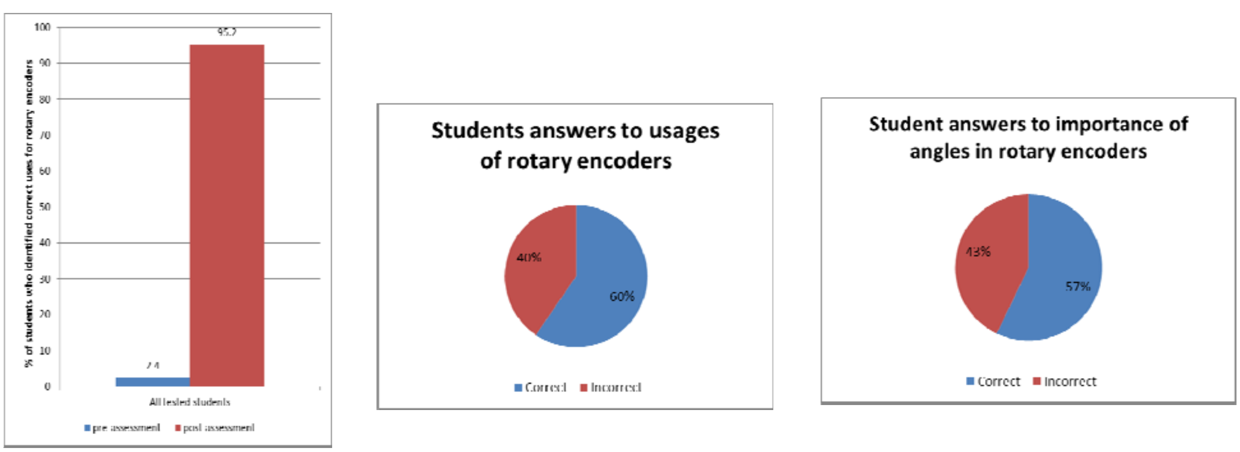


Figure 13: Sample in-class analysis work done by students relating inches and pixels measurements between the computer mouse and on-screen mouse cursor

Finally, the students transitioned from the lower cognitive domain to the higher cognitive domain (e.g., synthesis and evaluation) through discussions moderated by the graduate Fellow. For example, the graduate Fellow questioned the students about real-world situations in which rotary encoder can be useful and the students responded with "radio knobs, robots, cars, things that turn, etc." Moreover, higher cognitive domains were examined through qualitative survey questions Q2, Q4, and Q5 (see Table A.3). As shown in Figure 14(a), 95% of students synthesized a valid answer for Q2 on uses of the rotary encoders in modern devices. Next, as shown in Figure 14(b), 60% of students demonstrated a correct understanding of the rotary encoders on Q4. Moreover, as shown in Figure 14(c), 60% of students correctly evaluated the importance of rotary encoders on Q5. Although not all responses to these qualitative survey questions were correct, the students generally demonstrated an understanding of the importance of rotary encoders in measuring rotational movement.



(a) (b) (c)

Figure 14: Student responses to qualitative survey questions Q2, Q4, and Q5 in Table A.3

5. Conclusion

High quality education of K-12 students in the STEM disciplines is of paramount importance to train the next generation of scientists and engineers. Prior research has documented the effectiveness of Bloom's taxonomy[1,2] and robotics-based active learning[5,6] to yield higher-order learning and enhance student engagement of STEM concepts, respectively. There are many different ways through which K-12 students learn, retain, comprehend, and apply new information and knowledge. The ability to effectively transfer new information to students in an understandable and easy to learn manner, so that they are able to apply their learning, is a significant challenge faced by classroom teachers. The incorporation of lessons that actively engage students in the material gets them to physically interact with the subject matter. Such an approach intellectually stimulates students to engage in investigating and questioning activities within the scope of the lesson, which (1) leads to their increased comprehension through the application of the newly learned concepts and (2) allows them to form a long-term association with the learned concepts. This paper presents a first attempt to investigate the incorporation of the notions of Bloom's taxonomy in robotics-based active learning and the results of their applications in elementary- through secondary-level classrooms. Specifically, through three illustrative lessons, the paper demonstrates one approach to connect and address the entire cognitive learning domain of Bloom's taxonomy with robotics-based activities for engaging and transitioning students from lower-level cognitive domains to higher-level cognitive domains. Using pre- and post-lesson assessments and statistical hypothesis tests, the paper demonstrates modest gains in students learning and engagement in higher-level cognitive domains.

Preliminary results of this paper suggest several avenues for future investigations. First, it will be instructive to conduct a thorough comparison between the approach of this paper ("treatment group") and the traditional teaching methods ("control group"). Second, it will be useful to conduct a multi-week, in-class study where a series of related lessons, focused on a single topic, are designed and conducted to allow students to transition from lower-level to higher-level cognitive domains. By spreading out the lesson and activities over a longer time period, students will be allowed to enhance their knowledge and comprehension domains which are critical to transition to higher-level cognitive domains. Moreover, such an approach may be able to devote each class session to a single cognitive domain, allowing for the development of new higher-level cognitive domains by building on the previously developed lower-level cognitive domains. Such a study will also consider: (1) pre- and post-lesson assessments; (2) long-term retention of knowledge and skills across the cognitive domains; and (3) across-lesson demonstration of knowledge and skills across the cognitive domains for a lesson taught using the traditional teaching methods.

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Appendix A: Pre and Post-Lesson Assessments

Table A.1.: Engineering Design Principles using Biomimicry and Robotics

<table>
<tr>
<td>Pre-Assessment</td>
<td>Quantitative Assessment Questions
1. Susan and Sally are going to race their robots. Susan and Sally’s robot begin their race at exactly the same time. If Susan takes 22 seconds to finish the race, and Sally takes 24 seconds, who won? Please circle your answer.
Susan Sally


2. Susan and Sally are very competitive, so they are once again settling an argument by using their robots. Each robot is fitted with an ultrasonic sensor that will allow the robot to know when to turn around before hitting the wall and come back to the starting line. The wall is 4 feet from the starting line. Susan and Sally start at the exact same time from the starting line. Susan’s ultrasonic sensor’s threshold is set to < 12 inches, and Sally’s is set to < 23 inches. Susan’s robot takes 18 seconds to go round trip, and Sally’s takes 20 seconds. Who won the race in the least amount of time? Please circle your answer.
Susan Sally

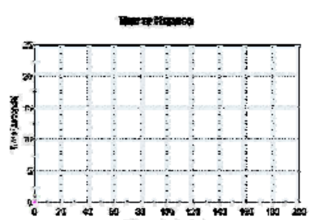

3. Using the information in question two, whose sensor should detect the wall first? Please circle one:
(a) Susan (b) Sally
4. Does increasing the sensor’s threshold value of Susan’s robot from < 12 to < 15 inches help her detect the wall sooner or later than if she kept it at 12 inches? Please circle one:
(a) Sooner (b) Later
5. Graph the following data of Sally testing her ultrasonic sensor’s threshold and how long it took her robot to detect the wall before triggering it to turn around:
Data (10cm, 22s), (20cm, 15s), (40cm, 9s), (80cm, 5s), (160cm, 2s)

6. Refer to question 5 and the graph. Which threshold distance does the robot take the longest to respond to the wall in? Circle your answer.
10cm 20cm 40cm 80cm 160cm</td>
</tr>
<tr>
<td>Post-Assessment
(includes quantitative questions 1-6)</td>
<td>Qualitative Assessment Questions
1. After this activity, do you feel more comfortable with measuring time?
(a) Yes (b) No
2. Did robotics help you understand measuring time better? Circle one and explain:
(a) Yes (b) No
3. Does changing the placement of the ultrasonic sensor on the robot affect the distance that the robot detects the object? Circle one:
(a) Sooner; (b) No Change; (c) Later</td>
</tr>
</table>

Table A.2.: Trigonometry using Robotics

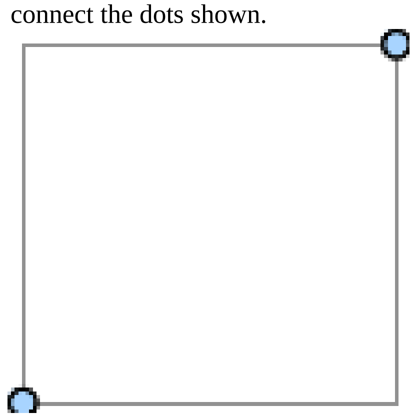
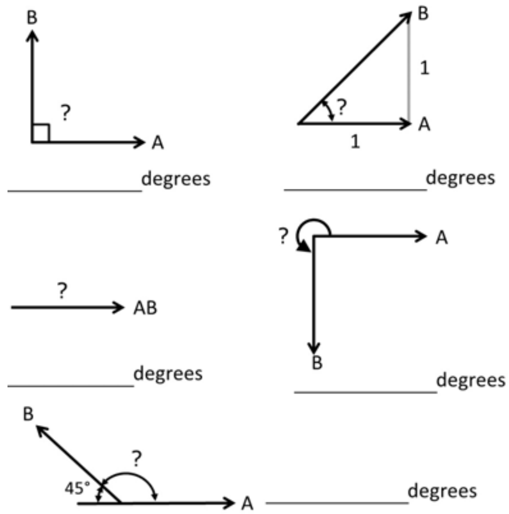
Pre-Assessment	Quantitative Assessment Questions	Qualitative Assessment Questions
	1. How is a triangle different from a square? 2. A triangle has _ sides (lines) in its shape. 3. Draw a diagonal line across the square to connect the dots shown.  4. Circle the kind of triangle that is obtained above (Q3). (a) Isosceles triangle (b) Equilateral triangle (c) Equiangular triangle. 5. If the length of the horizontal base shown in Q3 is 2 inches, then what are the lengths of the other sides? 6. If every angle between the sides of a square is 90 degrees, then what is the angle formed by drawing a line half-way through the 90 degree angle?	1. How much do you like geometry? (a) A lot (b) A little (c) Not at all (d) Don’t know 2. How much do you like math? (a) A lot (b) A little (c) Not at all (d) Don’t know 3. How often do you estimate the size of objects? (a) Weekly (b) Monthly (c) Not sure (d) Almost never
Post-Assessment (includes quantitative questions 1-6 and qualitative questions 1-3 above)		4. Do you feel more comfortable with triangles after completing this activity? (a) Yes (b) No (c) Not sure

Table A.3.: A Lesson on Human-Computer Interactions using Robotics

Pre-Assessment	**Quantitative Assessment Questions**	**Qualitative Assessment Questions**
	1-5. What do you think is the angle shown in each pictures? (Write the answer in degrees) 	1. Do you know what a rotary encoder is? (a) Yes (b) No 2. Have you ever used a rotary encoder? List some examples of devices that have rotary encoders. 3. How familiar are you with the topic of angles? Rate from 1 (not familiar) to 10 (very familiar)
Post-Assessment (includes quantitative questions 1-5 and qualitative questions 1-3 above)		4. Do you understand better how a rotary encoder works after this activity? 5. Why are rotary encoders used? 6. Why are angles important in using rotary encoders? 7. Did robotics (LEGO NXT) setup help you understand what a rotary encoder is better? (a) Yes (b) No