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A Robotics-Focused Instructional Framework for Design-Based Research in Middle School Classrooms

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FUNDAMENTAL: A Robotics-Focused Instructional Framework for Design-Based Research in Middle School Classrooms

1. Introduction

One of the main goals and strengths of design-based research (DBR) is to promote collaboration between education innovation developers (researchers) and education innovation implementers (teachers).[1] Specifically, DBR connects teachers and subject matter experts into a design partnership responsible for documenting and steering the learning environment towards the most effective course. In this vein, this paper reports on a project carried out by engineering education researchers in partnership with a seventh-grade classroom teacher. The classroom teachers are intimately familiar with their students and they possess the knowledge about various pedagogical strategies that are necessary to identify and define positive classroom outcomes. The iterative process of DBR models waves of educational innovation to create and improve teaching and learning theories while relying on empirical evidence to gain an understanding of how and why the designed learning works. Thus, our ultimate goal is to utilize the DBR process to develop theories that can be translated into classroom practices to enhance students' understanding of science, technology, engineering, and math (STEM) subjects while simultaneously inspiring them to pursue STEM careers. We employ DBR constructs, in the context of a robotics-based instructional framework, to support both student and teacher learning in several ways. The use of robotics serves to help stimulate an interest in STEM learning for students. In addition, robotics can help break the silos of the underlying disciplines of STEM to help realize the vision of integrating these disciplines. Such integration can show the students and teachers the relationships between different classroom topics and their relevance to real-world problems.

Whereas randomized controlled studies or cohort studies rely on a statistically significant comparison between groups to support claims or results of effectiveness, DBR studies typically forego such a methodology.[2] For several reasons, such a methodology may not be feasible or even desirable for certain educational innovations and contexts. The confounding factors between classrooms or schools, which may serve as treatment and control groups (different teachers, different students, etc.), are so pervasive that it may not be possible to correct for them in statistical analyses.[3] Therefore, as an alternative, the majority of evidence used in DBR is observational and consists of answers to questions such as:[2] "Do a significant number of people adopt and use the products of the research? Is its use (particular to the situation) sustained, cost effective, and perceived as valuable by the user?" Kelly[3] recommends that DBR answer the question, "Can this new set of methods establish boundaries (demarcations) between sound and unsound claims about learning and teaching?" In Kelly's view the main value of DBR, in addition to creating artifacts that can be used or tested more widely, is to generate hypotheses from observational data to be tested in later, larger-scale, quantitative scientific studies. Brown[4] points out that criteria against which to measure success of interventions or guide iterations in educational DBR should consist of development of traits which the school system is charged with teaching, e.g., problem solving, critical thinking, and reflective learning.

In this paper, we test the hypothesis that the flexibility and hands-on nature of a robotics platform will support different audio, visual, verbal (read/write), and kinesthetic learning styles,[5,6] offering teachers more versatility within lesson plans while effectively teaching STEM concepts to students. Despite a lack of agreement[7] within the education research community regarding categories or, in some cases, the existence of learning styles, currently the concept of learning styles is a widely-used operational construct for both research and pedagogical purposes.[8-10] As argued by Coffield *et al.*,[9] some of the criticism aimed at the use of learning styles stems not necessarily because of their complete lack of validity, but from the multitude of research groups[10] who have defined their theories and categories with a lack of an interdisciplinary approach and in isolation from each other. For the purposes of this study, we assume that auditory, visual, verbal, and kinesthetic learning styles[5,6] are valid constructs and thus we do not attempt to either prove or disprove the existence of learning styles here. Furthermore, we do not focus on assessing the individual learning styles of each student, we merely illustrate how robotics-based lessons and activities can encompass and support the breadth of aforementioned learning styles.

We show that through the use of DBR, *constructionism*, in which learners create their own knowledge, as in *constructivism*, but do so specifically through the process of building objects,[11] can be employed to create useful artifacts that stimulate both teacher and student learning. While the use of a robotics platform in STEM learning is not novel in itself, the use of a DBR process to evolve constructionism theories and the use of this tool to maximize student learning in STEM subjects is our novel contribution.

The methods of DBR are frequently mistaken for that of formative evaluation. Barab and Squire[12] note that a fundamental difference between the two approaches is that while DBR seeks linkages with existing theories and production of new theories, formative evaluation tests existing theories. Moreover, DBR is differentiated from formative evaluation by being contextually situated, e.g., in a classroom. In this spirit, within the context of a classroom, the present paper investigates the evolution of constructionism theories. Thus, our work differs from formative evaluation and embodies the practices of DBR with a high degree of fidelity.

2. Framework

The robotics learning sequence is composed of five phases: robot chassis, drive mechanism, transducers, robot motion, and programming.[13-15] Each phase has a specific role to play in the development of a robotic system and to create a bridge to span different subjects in the classroom. Within each phase of the robotic learning sequence the ADDIE model (consisting of analysis, design, development, implementation, and evaluation steps) of instructional design is used.[16] The analysis step provides the designer an opportunity to understand the learning environment and the learning challenges faced by the students and teachers. During the design step, learning objectives are specified so that the lesson can begin to take shape. Next, the development of the lesson takes place where the content and materials used are formed. The lesson is then implemented and evaluated.

Use of instructional scaffolding is integrated into the robotics learning sequence to help the students progress through the lessons while allowing them to internalize the knowledge needed to complete given tasks. Instructional scaffolding is an ideal starting point for this research as its methods parallel those used in DBR. During the progression of each phase of the robotics learning sequence, the students are encouraged and supported to create clear goals for that particular phase. As the students progress through each phase, they are given less guidance and instruction according to their level of understanding, an approach consistent with instructional scaffolding techniques. At the beginning of each lesson, a task is given to test the existing knowledge of students and to prepare their minds for the day's activity. The day's goal is prominently displayed and continually recited to the students. Students are taught key vocabulary terms and encouraged to use them throughout the lesson. Demonstrations of the robot activity are strategically used during the lesson to show students how to properly employ the robot for the task. When the teacher deems it necessary, direct instruction is given.

The first phase of the robotics learning sequence consists of the construction of a robot chassis. In this phase, students are given instruction on frames, symmetry, load, and center of mass. They are guided through the construction of the robot chassis and the design process using build and rebuild exercises. In the second phase, students create a drive mechanism for the robot. Lessons in this phase include gear ratios and motors. In the third phase, transducers are incorporated into the robot, thus allowing students to learn about the different sensors and actuators. The fourth phase deals with robot motion and includes lessons on translation and rotation. In the fifth and last phase, students learn to program their robots to accomplish different tasks. The breadth of knowledge covered in this sequence is important as it helps crosscut different aspects of all STEM fields within each phase. Applying several different math concepts while having fun and creating something tangible can help alleviate math fears in students and show real-world relevancy.

By employing the DBR processes, we refine the theory of constructionism, which is slightly different from that of constructivism.[11] Constructivism entails students building new knowledge from their experiences, e.g., by solving problems with their existing knowledge. In contrast, in constructionism students build new knowledge as they are engaged in making tangible artifacts. In this work, the constructionism approach is chosen because it aligns with robotics in a natural way. Specifically, new learning can occur as students use their existing knowledge to solve problems by creating robots, which are tangible objects. Lessons were developed to utilize the LEGO Mindstorms NXT educational robotics kit to engender a hands-on, interactive learning environment in support of the common core standards (CCSSM-7RP, 7NS, 7EE, 7G) and Next Generation Science Standards (MS-ETS1).[17,18] This allows students to work with robots to solve problems through their experiences while developing their own relationships between the problem and the solution.

Within the bounds of constructionism, we employed three learning theories to support our DBR process; Problem-Based Learning (PBL), in which students learn both content and thinking strategy through solving problems,[19] Cognitive Apprenticeship, in which learned material is integrated into the social and functional context of its use rather than in an abstract context,[20,21] and Anchored Instruction, in which knowledge is presented to students as a tool that can be used to solve problems rather than as classroom content in the absence of an applied context.[22]

2.1. Setting and Processes

Design research was conducted at an urban, inner-city middle school in Brooklyn, NY, that has a population of approximately 250 students attending grades 6 through 8. Approximately 70 percent of the student body is eligible to receive free or reduced-price lunch and 95 percent of the students are members of racial or ethnic minorities. Three seventh grade classes (77 students, total), comprising 85 percent of the entire 7th grade, participated in this study. This group of students consisted of 46 male and 31 female students. The classroom was divided into eight tables with room for four students each. Class sizes ranged from 25 to 26 students. The classes were each taking a half-year elective in *Advanced Technology* under the same teacher. Topics covered included PowerPoint, document sharing, internet safety and etiquette, copyright rules, and basic programming skills. Laptop computers were assigned to each student during classroom activities. During the previous year, a majority of the students had been exposed to additional programming curriculum, however their skills were at the beginner level. The three classes were taught concurrently over the span of several months to facilitate the iterative process fundamental to DBR methods. Sufficient time between each class allowed the teacher-expert team to make adjustments to the learning environment and implement these changes for the next class. Careful documentation of effective teaching methods to support students' diverse learning styles was maintained through each iteration to track the progression of the DBR.

2.2. Iterative Design Interventions

The most obvious criteria against which to measure the success of an educational intervention is the extent to which students are able to learn the intended content knowledge. For example, if one goal of the lesson is to teach math concepts, a pre- and post-assessment of students' relevant math skills can evaluate the success of the intervention. However, numerous factors, in addition to the presence or absence of the design-based intervention, contribute simultaneously to students' learning outcome such that it would be difficult to pinpoint the designed intervention, itself, as the cause of any differences in pre and post-test scores. Ferdig[23] describes three criteria for evaluating the performance of a designed educational intervention: (1) appropriate uses of technologies, (2) content learning outcomes, and (3) qualitative and observational data to examine social and emotional outcomes of the intervention. At each iteration, we used criteria one and three to alter the design of the lesson based on observational data of the teacher and researcher. As of this writing, sufficient reliable data has not been collected from pre- and post-lesson student evaluations to perform statistical hypothesis testing for content learning outcomes. However, we are able to summarize data from pilot pre- and post-tests to combine with observational data as a form of triangulation.

Initial Observations

Initially the first author, an engineering education researcher, observed the teacher in the classroom to gain insight into the learning environment and to observe student interactions and learning processes. During the traditional didactical instruction, many students were observed to be engaging in disruptive behaviors that involved violations of effective classroom norms and defiance of authority. As a result, the students' attention to lectures was often noticeably low both for the disruptive students and for their now frustrated peers. Once computer use was allowed, student behavior improved slightly. Although previously disruptive students now played games and listened to music, previously frustrated students were able to work and be productive at their own pace. These observations indicated that students preferred to be involved in their own learning process especially by conducting activities. To address the disruptive behavior, it was determined that breaking students into smaller groups could help maintain a social learning environment while simultaneously creating manageable group sizes for individual scaffolds to be implemented as needed.[24]

First Design Iteration

The first lesson involved a lecture to describe robots that students may have already been exposed to in their daily lives. The lesson described numerous uses of robotics in everyday life to create a link between the need for such devices and how knowledge of STEM fields can help meet needs for novel robotics devices. This brief overview to robotics was followed by a short video demonstrating a LEGO Mindstorms NXT robot that could solve a Rubik's Cube.[25] Next, the students were shown a variety of frame structures and led through a class discussion on the advantages and disadvantages of each. This led to the introduction of the problem we set out to solve—namely, how to create a system to sort blue and red balls contained in a tube by placing the balls of two colors into separate containers. With the problem defined, the class was organized into groups of four and worked to develop criteria such as inclusion of a light sensor, dimensions, and use of a section to hold a ball and constraints such as limited materials and time. Students were given LEGO robotics kits and asked to brainstorm possible solutions by building prototypes of a chassis, keeping in mind the criteria and constraints that they themselves derived in the previous step. This exercise was designed to provide the students with opportunities to arrive at individual solutions to the same problem.

During implementation of the first lesson it was observed that students were very interested in the video of the robot solving the Rubik's Cube but rapidly lost interest during the initial lecture. This resulted in disruptive behavior as observed during the previous lessons. During the robot building phase of the lesson, it was observed that some students were able to stay on task and work on building the chassis to meet the criteria and constraints of the design; however, many students were unable to build practical designs or devices for two reasons. First, students seemed overwhelmed with the amount of LEGO pieces available to them. This led them to either build impractical devices that did not meet any criteria or simply not build anything at all. Second, not all students had prior experience with LEGO parts, so in effect they did not know how to connect the components together.

These observations led the design team to make several changes to the way the lesson was conducted and how the students were involved throughout the process. First, the lack of interest and frequent disruptive outbursts by students led the teacher to suggest that the students be provided something to do throughout the lesson to keep them engaged. This suggestion was implemented through the use of a worksheet discussed in the second design iteration below. Second, the lecture was split into several short parts, with each being separated by activities that the students could conduct on the worksheet in groups or as individuals, depending on the activity. Third, the brainstorming session was changed from an open-ended build-task with the LEGO robotics kits to having students draw and explain their ideas first. Fourth, the problem associated with students' lack of experience with the LEGO materials was addressed by offering students building instructions for an existing design. The purpose of this series of changes was to prevent the students from disengaging from a long lecture or from a long self-directed activity. Moreover, an ancillary goal was for the instructors to be able to better monitor students' progress.

Second Design Iteration

Worksheets were provided to the students so that they could remain occupied and better visualize the process of the lesson. This also allowed the team to break the lesson down into smaller segments and show the engineering design process for a robotic chassis. The class discussed, as a whole (rather than as small groups as in the first iteration), the constraints and criteria for the system they were to design. Since students were initially reluctant to openly discuss the

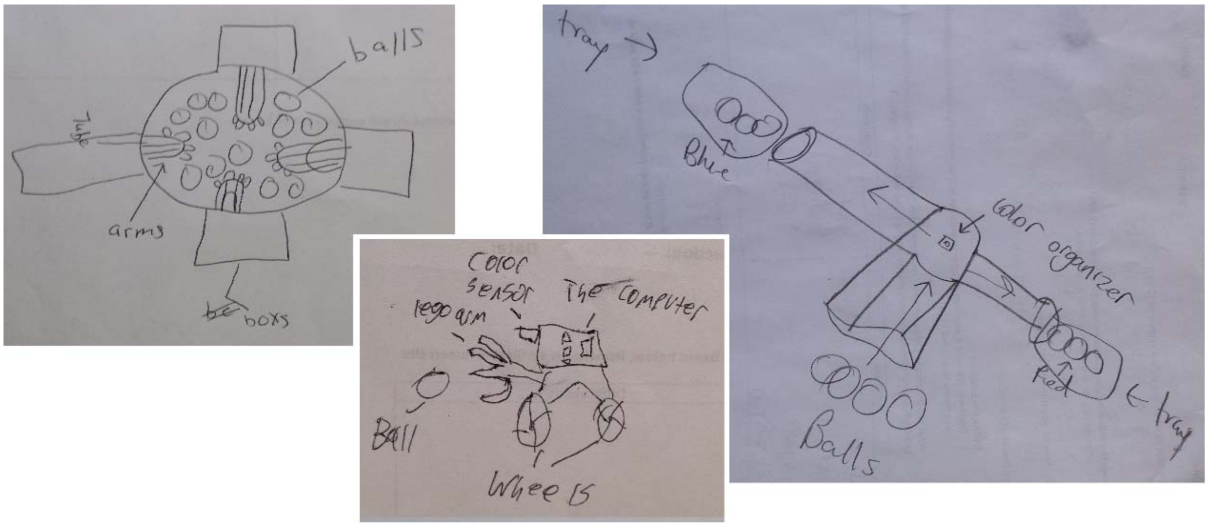


Figure 1: Ball sorter design ideas from the 7th grade students.

constraints, the teacher helped guide the discussion by asking questions such as, "What material are you using?" and "How big can you make it with that material?" This allowed students to understand the role of constraints in the engineering design process and to suggest additional constraints such as time. Then, in groups of four, they brainstormed possible solutions by drawing a design on paper that would meet the criteria given the constraints (see examples of students' work in Figure 1). In the previous iteration, this entire process was attempted while students were in groups using LEGO parts rather than drawings.

While students worked to brainstorm ideas, the instructor walked around the room to discuss individual group designs and to support students who were struggling, a process that is consistent with scaffolding techniques.[26] After the brainstorming activity was completed, the instructor guided the students in a group discussion about their designs, allowing student groups to share their ideas to compare and contrast with each other. Following the sharing of the students' paper-based designs, the instructor provided a suggested design (Figure 2), created by the first author who is a mechanical engineer, against which the students could compare their own designs. This form of modeling allowed students to see how their ideas were similar or different compared to a working example provided by the instructor.[21] The class discussed the pros and cons of each design. None of the activities up to this point involved using the actual LEGO components.

Next, each group built the suggested design out of LEGO components. For this exercise, the students were provided with step-by-step instructions for two reasons. One, to allow students who had little or no experience with LEGOs the ability to catch up and two, to allow the groups to complete the project without becoming frustrated. Note that it was not possible for the design team to include individuals with prior LEGO experience on every student-team to overcome other students' lack of experience. Moreover, this approach was followed based on the assumption that some of the previously observed disruptive behavior arose from students'

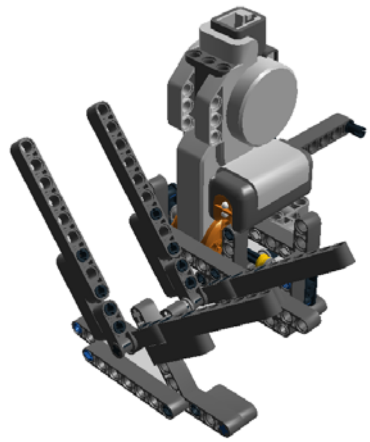


Figure 2: LEGO Mindstorms NXT ball sorter designed by a mechanical engineer.

frustration with the difficulty level and lack of guidance in the first design iteration.

With the implementation of these changes it was observed that disruptive behavior was reduced and students appeared more engaged in the lesson. Students were able to stay on task and the lesson flowed more smoothly with fewer interruptions or troublesome behavior. The breaks in the lesson for group discussion allowed the students to showcase their new knowledge including the use of vocabulary terms. The opportunity for the students to participate, each having the chance to voice his/her ideas in a safe, controlled environment, seemed to have a positive effect on the class. This social aspect of lesson-design is an important component of the learning process according to Ferdig.[23] The collaborative efforts of group work allowed students to observe how others learn and in turn helped individual students figure out new ways to expand their understanding.[19] When students were brainstorming in small groups the teacher was able to provide assistance to students who required additional support in understanding requirements for the design challenge. These observations were further augmented by both the verbal and nonverbal expressions of the teacher after the class was dismissed, indicating comparative success.

Utilizing cognitive apprenticeship, the comparison of student designs with an existing design created by a mechanical engineer, acted as a form of reflection for students to see how an expert might solve the same problem.[20,21] The use of PBL also allowed students to apply their knowledge in a more concrete manner than they were used to in other classes. To draw the students in and closer to the problem, the concept of anchored instruction[22] was discussed among the research team, and a lesson was planned as is discussed in the next section. Moreover, students started moving from the chassis design phase to the drive mechanism phase of the robotic learning sequence.

Third Design Iteration

The underlying theme for the lesson was robot motion with a specific focus on gear ratios. Through a PowerPoint presentation, within the framework of anchored instruction,[22] the instructor depicted a scenario in which a gear train is used to close a door behind which the students need to hide during a zombie apocalypse. This was to demonstrate how motion translates and direction changes through a gear train. For students with a broad range of skills and experience, anchored instruction has been shown to be effective when presented in video format, in part, because it allows students to form a mental model of the problem and "conditionalize" the knowledge.[27] In this spirit, the instructor explained, using PowerPoint illustrations, concepts of gear ratios, inputs and outputs of gears, and their relationship to gear speed. In a virtual room depicted in the PowerPoint there are gears, a robot, yardstick, paper, and worksheet. Next, each group was provided with these actual materials. The students were given a scenario in which they must use the robot to escape from a zombie horde, however the robot can only run for 3 seconds at a time and the students have a limited inventory of gears. The students were assigned the task of deciding which gear ratio would allow the robot to travel the farthest in 3 seconds. The activity consisted of each group exchanging various combinations and sizes of gears on their robot and then recording the distance traveled by the robot in 3 seconds. Students also recorded their observations during this exercise. The last section of the worksheet included a given distance traveled with the use of a 1:1 gear ratio. Students were then asked to fill in missing information to either calculate gear ratios based on distances or *vice versa*.

During the third iteration it was observed that students remained engaged in the material although the zombie theme was too exciting for the students and proved to be more distracting as it prompted side discussions about alternative solutions involving more violent methods. It was unclear as to whether students were more engaged due to the anchored instruction process or the need for a specific outcome for the problem itself. Furthermore, an anchored lesson requires a higher level of detail and planning than some alternatives and is thus not well suited within DBR as there are often many changes made in between iterations, which can be difficult to implement properly on a short timescale. This is not to say that anchored instruction is not effective, just that this particular instantiation of anchored instruction within the DBR framework, which necessitates quick turn-around between iterations, was deemed impractical.

In the course of data collection, students worked to measure the distance traveled by the robot with different gear ratios. It was noticed that some students were having trouble interlocking the gears although most groups were able to resolve this issue on their own or with minimal support from the teacher or researcher. Students appeared genuinely interested in discovering the best gear ratio to solve the problem; however, some groups lacked a proper methodology to acquire the data despite a table on the worksheet guiding them in a certain direction. This would be addressed in the fourth design iteration outlined below. Finally, although behavioral issues continued to occur they were reduced in frequency and caused less disruption for the rest of the class.

Fourth Design Iteration

In this design iteration, the gear testing section was explained in more detail and the testing process was broken down into more specific steps. These scaffolds helped students comprehend the methodology of the testing process, which in turn contributed to their understanding of the gear ratios and their effect on the speed of the robot. Use of zombie imagery was reduced to prevent outbursts observed in the previous design iteration. Students also worked to finish the worksheet that included more complex gear ratios. Feedback from the students was solicited on how the lesson compared to prior lessons and what they learned during the day's lesson (see sample responses in Figure 3).

The fourth iteration gave the research team insight into how well the lessons were impacting the students. In the questionnaire at the end of the worksheet, the students were found to be using more engineering vocabulary that had been introduced during the lesson and activity. Students were also able to identify relevant lessons in other classes that directly related to the robotics lesson they had just had, e.g., a math lesson on ratios and its relation to input and output gears (Figure 3). The pace of the class was noticeably controlled by the students' progress through the worksheet. In fact, the pace was seen to have increased from initial lessons that did not use any worksheet. The breakdown of the testing section helped students who were previously struggling and even increased the speed at which other students tested the gear ratios.

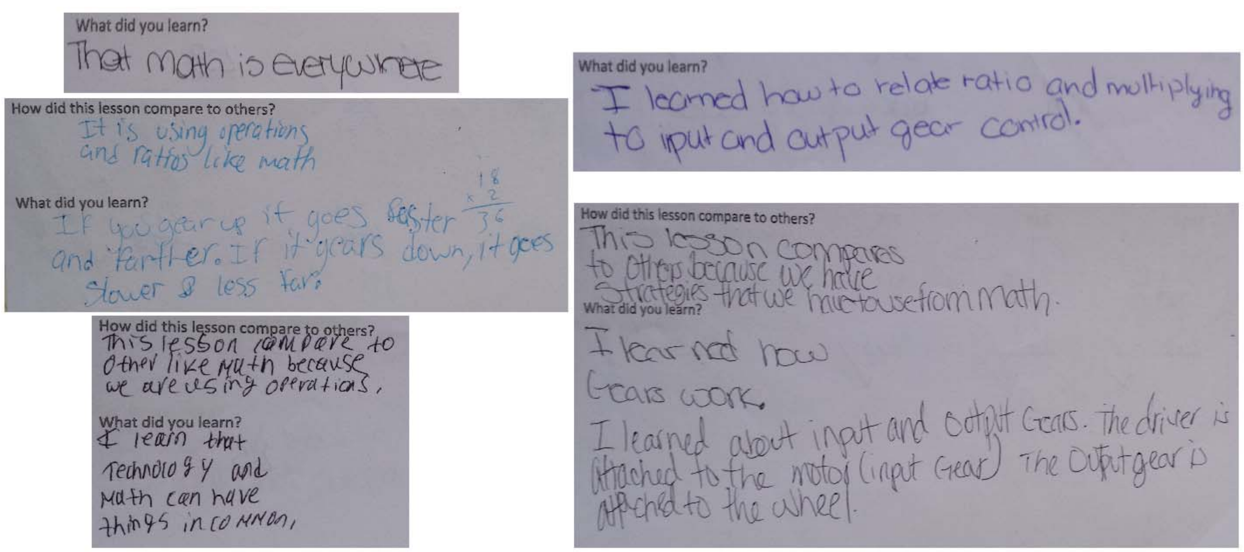


Figure 3: Student feedback for anchored lesson on movement.

The increase in engineering vocabulary usage prompted the design team to add a written vocabulary section to the worksheet to allow students to further grasp new terms. A stronger emphasis on verbalizing explanations was decided on for the next lesson. The reduction of the zombie imagery had a positive effect on the behavior of the classroom and did not seem to diminish their motivation to solve the problem; therefore it was omitted from future lessons. Future lessons would still focus on a central problem of being able to sort through different colored balls.

Fifth Design Iteration

The fifth design iteration took place in the transducers phase of the robotics learning sequence. Here students were brought back to the problem of sorting different colored balls. Throughout the lesson students were introduced to new engineering vocabulary terms for which they wrote definitions on their worksheets. The lesson began with students finding the average value between two different numbers that were implied to be sensor readings. Students were then shown a video in which a robotic device organizes skittles into cups of different colors;[28] this showed a fun application of the given problem. On the worksheet provided, students were asked to identify the number of sensors in the video and their functions. To give the problem more meaning, students were informed about robotic devices that utilize sensors to help sort recycled materials. Next, the instructor defined transducers and gave examples from the different LEGO robotics components, followed by a more detailed look at how the light sensor works. To help students better understand the concept of reflectivity, the class discussed summer attire with respect to fabric color. Students were able to identify with the concept of darker clothing being hotter on a sunny day compared to lighter colored clothing. This helped students internalize the knowledge about the light sensor's functionality and conceptualize the underlying scientific principle of reflectivity. The ball sorting problem was again presented to the students and in their groups of four they were asked to write down ideas about how they could sort the balls by color. The instructor walked around the room to assist students and observe the methods being discussed. Next, the groups were given their robots with a light sensor already attached and instructed on how to obtain measurements via the LEGO Mindstorms NXT's LCD screen. Students were then given one blue and one red ball and asked to measure and record the amount of reflected light each gave off. Lastly students were given a series of colors for which they had not previously measured reflectivity with their robot, and were asked to rank the colors in the order of least to most reflective, based on knowledge gained both during the class discussion and their experiment and the collected data using the blue and red balls.

This iteration showed the design team that the increased emphasis on vocabulary was quite effective in stimulating more meaningful discussions about solutions to the presented problem. Some students were also able to formulate solutions to the problem by linking together information from this and previous lessons. Students' increased use of vocabulary terms was

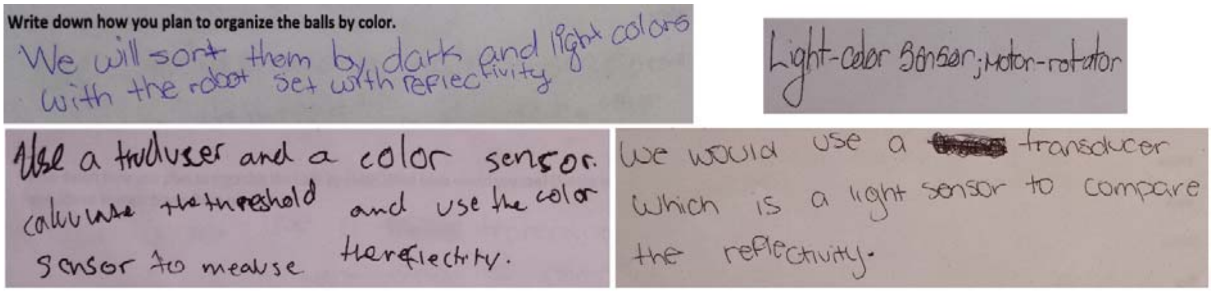


Figure 4: Selection of student responses for written brainstorming

evident after the inclusion of more written vocabulary terms during brainstorming as seen in Figure 4.

Asking students how they would solve this problem allowed them to discover what knowledge they needed in order to be successful. Working at the forefront of their thinking helped to motivate students when the time came to learn about how reflectivity works.[29] This idea also resonated when students were trying to measure the reflectivity of each ball. Through a series of questions, the students were guided to the realization that they should measure the reflectivity at the same distance for each ball and that the measurements offered better results at closer distances to the sensor.

3. Outcomes

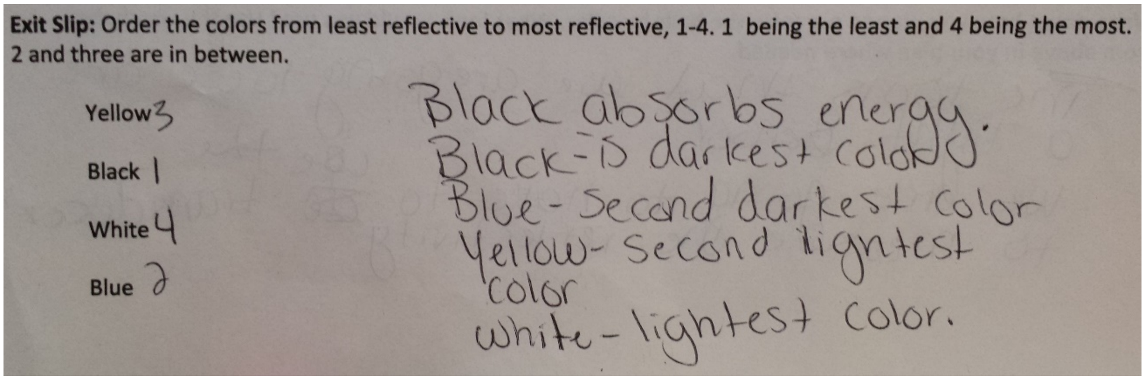
During the course of this research the research team observed many things that worked and others that did not. It was deduced that students responded best and contributed more when they were given an engaging problem to work on; it did not seem to matter whether that problem was based in reality such as a ball sorter or fictional such as a zombie escape vehicle, just that the problem offered significant relevance to the students. This is further supported through pre- and post-testing data collected for the movement lesson, which included work with ratios. In the pre-test, students were asked to reduce four different ratios that ranged in complexity. Students' work showed varied and sometimes lengthy methods of solving these problems with more than half of students failing to even answer the questions, yielding an average pre-test score of 35 percent. After the problem was defined in a meaningful context, through the zombie escape scenario, the worksheet eventually circled back to five different ratio reduction questions. This next series of ratio questions were answered more efficiently, almost intuitively, with more than 80 percent of students solving four or more questions correctly, resulting in an average post-test score of 72 percent. Framing the questions as problems with an actual purpose helped to draw students in, making them more interested in finding the solution to the problem.

Utilizing robotics to build and interact with a physical object gave students the ability to see how their knowledge can be used to produce something tangible and meaningful. When combined with PBL and constructionism, the robotics platform was rendered extremely effective in engaging and retaining students' attention. Constructionism helped students to develop conceptual understanding in a more physical manner. Specifically, when building a frame for the ball sorter, as students sought to develop physical realizations of their ideas, the process allowed their mistakes to surface quickly, which led to modifications and improvements in their initial ideas. Students were also able to compare and contrast with their peers' designs in an intuitive manner. Finally, the physical presence of the robots offered a sense of pride to students who always seemed slightly happier to see their robots at their tables as they arrived to class.

Classroom lectures and discussions helped to serve auditory learners. Moreover, the classroom practice of having new concepts and formulas recited by all students as a group provided additional support to auditory learners. Use of PowerPoint presentations, which included formulas, diagrams, pictures, and animations, helped facilitate visual learning. Inclusion of the worksheet benefitted the students in two ways. First, students who tended to become bored or lost in the lecture were given tasks that helped them to follow along with the lesson. Furthermore, students who were more advanced could work ahead of others without becoming frustrated by the lack of progress. Second, the worksheets allowed verbal learners the ability to understand concepts through vocabulary and other exercises on the worksheets. The use of robotics helped to reach the kinesthetic learners by allowing them to see the outcomes of the math and science principles learned in the classroom through the physical interaction with the robot. In particular, it was observed that the interaction of the students with the robot gears helped them to accurately predict the distance a robot would go when using a different gear ratio.

Through the use of PBL students were able to discover the requisite knowledge to solve the particular problem they were presented with. During a discussion before the sensors lesson, students were unable to conceptualize how the light sensor could be used to differentiate between two colors. After utilizing the robot to measure reflectivity of red and blue colored balls, the students were capable of deducing the reflective properties of other colors and how those values relate to color identification (Figures 5 and 6). When these pre- and post-testing activities are compared with observations made by the design team, there is a strong indication that the students' understanding was a result of integrating robotics with PBL.

The use of cognitive apprenticeship helped students to visualize how a professional begins to solve similar problems and the different methods used to guide the individual to a solution. By combining and refining different methods through DBR, the team was able to increase students' engagement in the classroom and reach more students than previously. Observations show that students also responded well and adapted to the requirement of group PBL by varying their response methods. Specifically, through the iterations, students changed the methods of response from a more individual basis to a social approach.

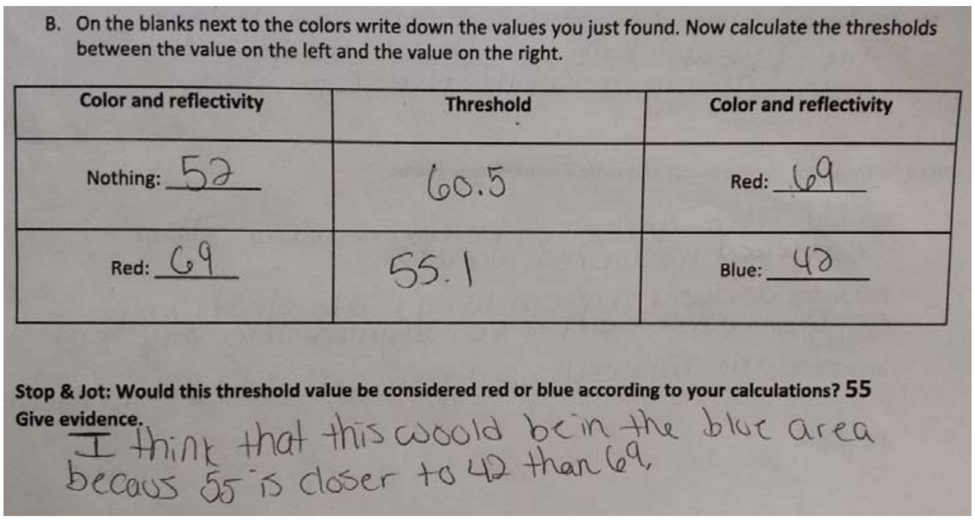


Exit Slip: Order the colors from least reflective to most reflective, 1-4. 1 being the least and 4 being the most. 2 and three are in between.

Yellow 3
Black 1
White 4
Blue 2

Black absorbs energy.
Black-is darkest color.
Blue - Second darkest color
Yellow- Second lightest color
white - lightest color.

Figure 5: Example of conceptual understanding of reflectivity after sensor lesson.



B. On the blanks next to the colors write down the values you just found. Now calculate the thresholds between the value on the left and the value on the right.

Color and reflectivity	Threshold	Color and reflectivity
Nothing: 52	60.5	Red: 69
Red: 69	55.1	Blue: 42

Stop & Jot: Would this threshold value be considered red or blue according to your calculations? 55
Give evidence.
I think that this woold be in the blue area becaus 55 is closer to 42 than 69.

Figure 6: Color estimate made after conducting measurements with the robot.

4. Evolving Principles

Although this particular research was conducted in an urban, inner city classroom there are several principles that transcend the local setting which are beneficial to other educators. First, it is best for the educator to be aware of any assumptions they might be making about what types of knowledge the students already possess. This is particularly important if the instructor is not from the same area or background. In our research there were assumptions made about the types of materials, experiences, and technologies to which the students had been exposed. For example, based on the assumption that all students had previously used or played with LEGO, no initial instruction was provided on LEGO brick assembly; however, some students had difficulty assembling LEGO pieces due to their lack of exposure to it.

Our research revealed multiple instances in which student behavioral problems seemed related to frustration on the part of the students and were alleviated by subsequent design changes. The DBR context allowed the team to alter aspects of a planned lesson when frustration was evident.

We found that it was more effective to break lessons into smaller components, providing some instructions or content interleaved with student activity. While the lessons originally seemed to have been developed to allow this, they were divided into even shorter segments after the first iteration allowing for increased scaffolding as needed by the students. We assumed that working in small groups would allow all students to participate, but disruptive behavior within groups prevented even the most enthusiastic students from contributing their ideas. When students were first able to contribute their ideas while the entire class was together and discussion was regulated by the instructor, behavior and discussion in the smaller groups that followed was more productive. Similar to the frustration alleviated when lessons were broken into smaller components, presenting student groups with a subset of LEGO kit pieces rather than the entire kit at once improved student participation and behavior. It appeared that the large number of kit components proved overwhelming for some students, such that they gave up on the assigned task. A more manageable number of pieces allowed the students to participate in the constructionist learning process, which requires successful building of artifacts. Anchored instruction was not as effective as we had hoped, to some extent having the opposite result from the intended. The zombie story line in the PowerPoint presentation, designed to engage the students and motivate them to find a solution to a problem, instead distracted them. However, inherent in the DBR process is the ability to alter a lesson plan with the goal of optimization.

It is important to guide students to access and activate knowledge they already have so that they can better understand what else they need to know or learn. Doing so will encourage them to strategize solutions in a more meaningful way, promoting critical thinking skills and lifelong learning. Often, students' typical classroom experience involves reluctance or even fear of giving an incorrect answer. In contrast, throughout the engineering design process and PBL scenarios we can learn a lot, sometimes more, from the mistakes or less than ideal paths we take along the way to our final design or solution. Thus, it is important for students to become comfortable trying a solution based on the knowledge they have, possibly failing, and being able to understand the answer or error they might obtain. The ability to identify an incorrect solution is a useful skill to have as it will allow the students to re-examine their solution methods or decipher what information they are missing to arrive at a solution that makes sense.

5. Conclusion

Throughout the first three phases of the robotic learning sequence, DBR methods were used along with constructionism, PBL, cognitive apprenticeship, and anchored learning to develop artifacts that help broaden students' understanding of STEM subjects while simultaneously reaching auditory, visual, verbal, and kinesthetic learners. Both the appeal and difficulty of DBR is that the learning environment comes alive as it is continually changed and adapted. In this manner, aspects of the lesson, learning environment, or both can be modified to meet the students' needs; however, this creates more work for the teacher. Constructionism was an ideal match with the robotics learning sequence as it naturally provided students a way to visualize their own knowledge and the knowledge of their peers. This supplied both motivation and supplemental knowledge of alternative solutions to similar problems. Furthermore, the use of PBL is instrumental in the classroom as it offers context and motivation for students to learn when carried out thoughtfully.

Providing the students with an opportunity to contrast their paper designs with an expert-designed ball sorter modeled the approach of cognitive apprenticeship, revealing an expert's thinking and solution strategy to students, allowing them to construct their own methods of problem solving and enhancing their critical thinking skills. It was realized that DBR methods are not best suited for anchored instruction on a short timeline as this method requires several changes to be made while the lesson is adapted and evolved. This becomes an arduous task as anchored instruction includes a highly detailed and immersive storyline which often cannot be altered on a short timeline or with a small budget.

The robotics learning sequence helped foster a learning environment that was conducive to auditory, visual, verbal, and kinesthetic learners. With every iteration it is possible to modify the lesson to influence the different types of learners present in the classroom. The format of our lesson vastly changed over subsequent iterations creating a learning environment that is now beginning to truly engage students and excite them about STEM subjects. Future work will investigate the effects of activities, redesigned on the basis of design iterations of this paper, with a new group of students to seek further evolution and refinement of these theories. Further use of DBR methods along with the robotics platform can help link with and evolve other learning theories and produce artifacts and guidelines for classroom practices that may prove useful to other educators. A certain approach that works in one environment may not work in another, therefore, as suggested by design researchers, it is important for researchers and educators who perform this work to share their findings with others so that a better understanding of theories and methods can be established and applied to varied situations.[30]

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