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Using Robotics as the Technological Foundation for the TPACK Framework in K-12 Classrooms

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FUNDAMENTAL: Using Robotics as the Technological Foundation for the TPACK Framework in K-12 Classrooms

1. Introduction

Recent years have seen increasing reliance by educators on the use of educational technologies to engage student learning of science, technology, engineering, and math (STEM) content. The proliferation of technology to facilitate effective pedagogy of STEM content has broadened the notion of "pedagogical content knowledge" (PCK[1]) to produce the conceptual framework of "technological pedagogical content knowledge" (TPACK[2]). Specifically, the TPACK framework emphasizes teachers' use of technology to assist students in comprehending content which may be pedagogically challenging. This framework consists of three domains: technology-, pedagogy-, and content-knowledge, and it includes the relationship each makes with one another. Technology, a product of applied science and engineering, is broadly defined to include technological artifacts and the system of knowledge domains, processes, techniques, skills, tools, and organizations to design, produce, and operate such artifacts.[3,4] In this work, we use technology to refer to the authentic and unique tools, techniques, skills, and knowledge of applied science and engineering, which are used by practicing scientists and engineers and can be appropriately adapted to promote learning in a classroom setting. Moreover, pedagogy refers to the different theories associated with effective teaching and learning methods as well as the assessment of student learning.[1,2] Finally, content refers to the fundamental concepts, theoretical principles, and organization frameworks of a discipline treated in the learning environment. By exploiting the synergistic interactions among the three knowledge domains of technology, pedagogy, and classroom content, the TPACK framework can allow technology to be used as an effective pedagogical tool for creating and presenting novel representations of disciplinary knowledge that are more readily accessible to students.

In this paper, we consider the use of the LEGO Mindstorms EV3 robotics kit to allow teachers to create unique and varied representations of disciplinary content in science and math. The use of robotics in the classroom can generate excitement and encourage participation in STEM learning for a wide range of students.[5] Thus, this paper considers a novel instantiation of TPACK with robotics through three illustrative examples of classroom lessons in physics, biology, and math. Whereas previous TPACK research has focused on teachers' readiness to implement technology,[6] suggested qualitative assessment tools,[7,8] and potential criteria to assess the implementation,[8] this paper puts these concepts into practice, providing descriptions of three lessons, including the rationale for the use of the TPACK framework in their development, and a comprehensive analysis of the classroom implementation of one lesson. This analysis includes teacher and researcher observations, pre- and post-assessment of learning, and an evaluation of the technology in pedagogy.

The first lesson is designed to provide secondary school students with a new representation of concepts related to energy, e.g., forms, transformations, and conservation of energy. Many students have difficulty comprehending the law of energy conservation due to its abstract nature. A major source of students' confusion stems from their inability to visualize a system containing both kinetic and potential energy, simultaneously. The lesson described in this paper illustrates the application of a zipline robot[9] to evaluate and display the energy states of the robot along an inclined path. This lesson offers an engaging activity through which students can visually examine and verify the law of conservation of energy using the zipline robotic system. Robotics provides a suitable platform to represent many biological concepts, as well. For example, species-specific types of locomotion may be explained by biological adaptation. Similar to the previous example, there are many challenges in demonstrating characteristics of biological adaptation. However, through the use of robotics students can manipulate and simulate the significance of different anatomical features. In this spirit, the second lesson employs situated cognition[10] to enhance students' comprehension of concepts within the phenomenon of biological adaptation. This activity provides students an opportunity to formulate hypotheses regarding advantages of various locomotive features for animals in an arctic environment.[11] In this instance, the robot is used as a physical representation of an animal and an inquiry-based process is used to enhance students' learning experience. The final lesson addresses students' difficulties with pattern recognition by providing a physical representation of a common mathematical sequence. Specifically, a mobile robot is used to trace the outline of a path representative of the Fibonacci sequence.[12,13] This lesson allows students to visualize the rapid expansion of the Fibonacci sequence and engages them in performing measurements with rulers. In each of the lessons outlined above, the use of the TPACK framework has improved the learning process through technology integration, offered an engaging learning environment, and addressed important content knowledge, as shown in Table 1.

The above three lessons illustrate the ability of a technology, the LEGO Mindstorms EV3 robotics platform, to help students visualize and access typically abstract physics, biology, and math content knowledge. These integrations of technology into the classroom allow for the STEM content to become more readily accessible to students, elucidating, validating, and encouraging the use of a robotics-based platform for technology integration using the TPACK framework. A comprehensive analysis of the biological adaptation lesson conducted with a 3rd grade class is provided to demonstrate the benefits robotics affords as an educational tool. This analysis includes pre and post-assessments of content knowledge of students, as well as teacher and researcher observations on social and emotional responses of students. Note that this example is not intended to set any limit on the grade-/age-levels that a robotics lesson, in general, and this lesson, in particular, can potentially address. Finally, recommendations for future research, implementation, and assessment are provided.

Table 1: An overview of technology integration, pedagogical benefits, and disciplinary content addressed through the designed lessons.

	Energy	Biological adaptation	Fibonacci sequence
Technology	– The zipline robot allows students to record quantitative measurements of the transformations of energy state – The ability to observe changes in energy states improves students understanding – Represents disciplinary content in a novel manner	– The walking robot offers a suitable platform for inquiry-based learning through a physical analog – Students generate interest in the “survival” of an inanimate object (technological educational tool) through an embedded storyline	– The mobile robot allows students to recognize seemingly unrecognizable patterns – Technology offers a visual representation of content traditionally difficult to represent visually – Promotes participation and group collaboration
Pedagogy	– Technology affords the ability to address the quantitative nature of energy transformations through hands-on experimentation – A visual representation of energy transformations allows students to generate a deeper understanding	– Students remain engaged throughout the lesson through situated cognition techniques – The embedded storyline produces a relationship between the student and the educational tool (robot) – Group participation allows students to succeed through collaborative learning	– The use of the robot as an educational tool helps students to visualize patterns in a unique way – The production of artifacts (drawing of the path) throughout this lesson improves the learning process by visually representing the sequence
Content	– Research shows students have difficulties comprehending concepts related to energy – Improved lessons related to energy are important due to the personal, social, and environmental impacts of energy usage	– Students find concepts related to biological adaptation difficult, calling for alternative perspectives on the subject matter – Research suggests teaching biological adaptation at earlier ages will help	– Pattern recognition and awareness of such structures is critical to mathematical competence with young learners – Perceptual learning does not typically address pattern recognition in standard math instruction

2. Motivation

According to Shulman,[1] PCK entails fluency in using “the most powerful analogies, illustrations, examples, explanations and demonstrations,” to represent a subject so that it is accessible to learners. Many STEM concepts are more abstract than other disciplinary content that K-12 students are required to learn. Modern technologies are often used to enhance teachers' PCK of STEM subjects and with the increasing reliance on digital technologies for teaching and learning, education researchers have studied the "triad"[14] of technology-pedagogy-content. Driven by the promise of technology to improve classroom teaching and learning and prepare students for STEM workforce readiness, in recent years, schools have witnessed an increase in spending on technology. However, it is of paramount importance that teachers receive effective professional development on the use of these technologies to improve their students' learning. The representation of abstract knowledge in a concrete and accessible manner through the effective use of technology has been termed as the TPACK framework by Mishra and Koehler.[2,14] The TPACK framework requires that education research on the integration of technology, as a pedagogical tool, produces guidelines to facilitate teachers' ability to learn not only how to operate technology but how to use it most effectively in the classroom.

Past efforts have resulted in a "pedagogically unsophisticated" approach to technology integration, which Papert[15,16] describes as "technocentric." Specifically, technocentric approaches to technology integration begin with examining a given technology for its value and limits, and then determining how the technology can be integrated to enhance pedagogical outcomes, rather than determining how technology integration could best illustrate disciplinary content. This approach does not adequately address PCK issues, directly. In contrast, in this paper, the application of the TPACK framework to robotics begins with identifying three STEM-related topics that have proven to be pedagogically difficult, followed by design and implementation of technology-driven lessons to provide more concrete examples of the STEM content than might be possible in the absence of the technology. The three topics presented in this paper (energy, biological adaptation, and mathematical sequences) often create pedagogical difficulties when traditional instruction methods are used, such that students are unable to understand or retain the content knowledge and teachers subsequently seek and construct alternative approaches to teaching these topics. In such cases, robotics can serve as an instructional tool to provide students with the ability to visualize and understand that same content.

3. Lesson Descriptions

3.1. Energy—Forms, Transformations, and Conservation

This lesson illustrates the integration of robotics as a pedagogical tool to teach students kinetic and potential energy, in terms of state variables. In response to increasingly significant personal, social, and environmental impacts of energy usage, a fair amount of recent research[17-22] has focused on the difficulties in teaching abstract concepts of energy. Heron, Michelini, and Stefanel[20] argue that a major challenge in constructing lessons addressing energy concepts is developing qualitative representations, without diluting the quantitative nature of the subject. The authors[20] suggest four major pedagogical goals that help define this problem: discussion of different forms of energy (kinetic, potential, elastic, etc.), recognition of energy as states (properties) of a system, identification of energy transformations, as well as observation and measurement of energy transformations to validate energy conservation.

Students are often unable to understand potential and kinetic energy from a system's perspective; for example, a system can contain both forms of energy simultaneously. This issue cannot be easily addressed using traditional pedagogical techniques, however, by integrating robotics technology into the curriculum, teachers can create an engaging and visual representation of such a system. Heron, Michelini, and Stefanel,[20] support Carr and Kirkwood's[21] proposal that the teaching of energy concepts should be supported with examples in which observable changes are apparent, such as a suspended object falling from higher to lower positions. This avoids misunderstandings inherent in purely static[20] examples. Brook and Wells[22] further support this claim, elaborating that the purpose of these experiments is to reinforce the notion of transformation and conservation. Guided by these prior researchers, this lesson makes use of a zipline robot, shown in Figure 1, to provide students with a new representation of a system's energy states, demonstrating energy transformation through the use of a dynamic system.

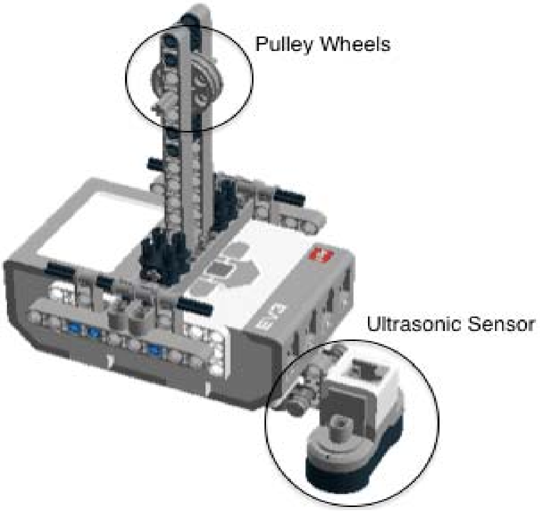

Figure 1: The zipline robot instrumented with sensors used to evaluate the energy states of the robot.

To provide students with an introduction to potential and kinetic energy, from a systems perspective, this lesson begins with an oral presentation and a demonstration to support the discussion. As stated previously, discussion of different forms of energy is critical for students to develop further understanding of conservation and transformation aspects of energy.[20] First, a formal definition of a system and two forms of energy (kinetic and potential) are explained to the students, allowing them to differentiate between these forms of energy. These definitions are then reinforced through examples of systems that contain potential and kinetic energy; to illustrate these topics, the energy states of a falling object are discussed. Concepts from this example are then reinforced through the use of a visual representation. A ball is used to represent the "falling object" illustration provided earlier in the lesson. The ball is dropped from a set height, allowing the process to be analyzed through a group discussion, intended to identify the transformation from potential to kinetic energy. To transition into the robotics portion of the lesson, students are encouraged to discuss and generate hypotheses about the energy states of a person on an inclined zipline. The discussion of different forms of energy and the demonstration focusing on energy transformation are only intended for students to become familiar with the content, while the following zipline robot activity provides necessary experimental evidence and validation of energy conservation with numerical data.

The "usefulness" of energy is closely related to the ability to quantitatively[20] measure the transformation of energy states. Therefore, the ability to observe the change of energy states is critical to understanding these concepts. In turn, the measurement of the kinetic and potential energy of the zipline robot provides students with a critical component in the understanding of energy states, transformation, and conservation. The zipline robot is constructed to move under the force of gravity along an inclined zipline path. The robot is instrumented with an ultrasonic sensor and a program running on a PC wirelessly polls sensor data allowing the robot's height and speed to be evaluated at any desired position along the zipline path, as shown in Figure 2. As Ferdig[7] mentions, active learning can be enhanced by technology integration, which is supported through this lessons' use of hands-on pedagogy with the zipline robot. Students in groups of three to four use the zipline robot to investigate the conservation of energy as the robot traverses the zipline. Students are responsible for collecting position and velocity data at multiple points along the zipline path and using these data to verify that the energy is conserved. This ability to represent disciplinary content in a novel manner that is visually accessible and allows hands-on experimentation can solely be attributed to the technology integration.

3.2. Biological Adaptation

This lesson demonstrates the implementation of robotics under the TPACK framework to teach elementary school students the complex concept of biological adaptation. Standard pedagogical approaches to teaching students biological adaptation appear to fall short. Clough and Wood-Robinson's[23] analysis of secondary school students' understanding of biological adaptation argues that "students find the subject area difficult" and suggests that alternative perspectives of the subject matter would benefit students. This study also recommends that these concepts be introduced much earlier in the science curriculum.[23] Currently, the National Science Education Standards[24] offer science content standards for grades 5-12, omitting the incorporation of

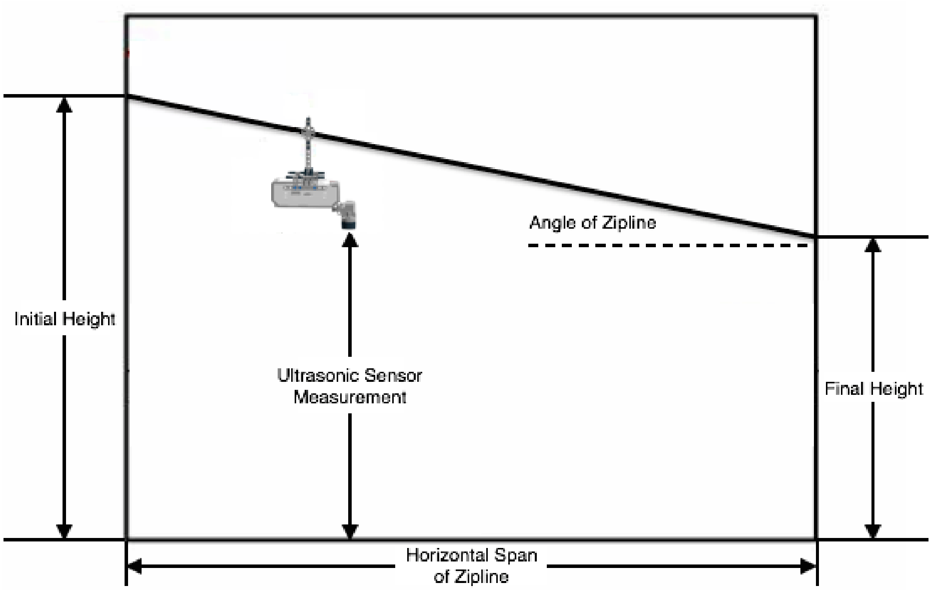

Figure 2: Schematic of zipline robot and necessary geometric properties to determine the energy states of the robot along the inclined path.

disciplinary content for biological evolution in the K-4 curriculum. However, Wagler[25] also supports Clough and Wood-Robinson's recommendation that concepts of biological evolution, which encompass adaptation, should be introduced in the classroom at a much earlier age. Specifically, Wagler[25] has constructed a set of science content standards to address biological evolution in the K-4 curriculum.

Significant prior research has been conducted to identify student misconceptions and difficulties in understanding concepts of biological adaptation.[26—28] It appears that possession of PCK, on its own, may not be adequate for educators to present the biological adaptation content in a manner accessible to students. In response, this lesson exploits the use of a four-legged mobile robot and situated cognition[10] techniques to produce a storyline embedded with important concepts of biological adaptation. This approach allows students to actively participate in the activity, while generating an understanding of the information presented. In this example, the robot is used as a physical representation of an animal and inquiry-based learning is used to enhance participation and comprehension. Such use of a mobile robot to introduce students to biological adaptation creates an engaging and innovative learning environment, which allows the content to become more accessible.

Initially, students are introduced to the lesson's content through a PowerPoint presentation incorporating pictorial examples of adaptation in animals and two other concepts which are necessary to understand adaptation: heredity and basic needs for survival. Two illustrations given of inherited traits that are adaptations to a specific environment are the unique fur coloration of the snow tiger and the use of echolocation in the common vampire bat. This lesson focuses on locomotive features; therefore, the remainder of the presentation emphasizes different types of locomotion: walking, swimming, and flying. Species that utilize each form of locomotion are discussed. Biological adaptation is linked to environmental conditions to which an animal is exposed and that impact their ability to survive and reproduce.[29] Once students have been introduced to the general topics associated with adaptation, a classroom discussion ensues, encouraging students to evaluate the needs of an animal in a snow filled environment. This provides students with an opportunity to generate hypotheses about the robot's performance during the subsequent hands-on part of the activity. Students are then provided with worksheets that can be used to help assess their current comprehension of the content.

Next, the four-legged robot is revealed to the students and, to make a clear connection between the robot and the previous discussion of adaptation, the robot is described to the students as a "physical analog" of the snow tiger. To set a premise for inquiry-based learning with the robot, a storyline is implemented; illustrating that the "snow tiger" is hungry and needs to find food to survive. The robot uses two different sets of legs in this lesson; the first set of legs has a pointed base while the second set of legs has a wide attachment at the base (Figure 3). A tray filled with cotton balls is used to model the snowy environment that the snow tiger must traverse to obtain the food it needs to survive. Students in groups of three to four investigate differences in locomotion when either the pointed-base or the wide-base feet are attached to the mobile robot. Specifically, for each type of feet, they measure the distance travelled by the robot through the cotton ball terrain in 30 seconds. During this part of the lesson, questions are posed to students regarding the benefits of each type of feet in the "snow," how the two types of feet might impact the animal's ability to survive, what may drive adaptations in foot shape, and so on. This activity's use of the mobile robot as a pedagogical tool and its use of situated cognition for inquiry-based learning allow students to generate deeper understandings of the content. Following the lesson and activity, students are again provided worksheets to help assess their understanding and retention of the content.

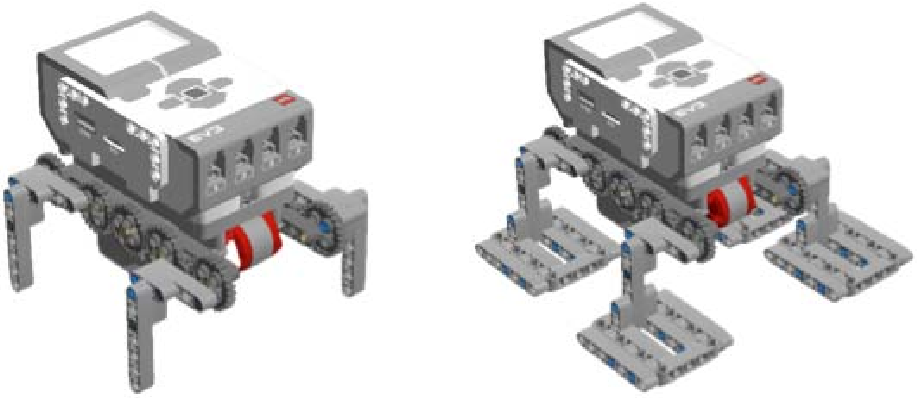

Figure 3: Displayed are the pointed-base legs (left) and wide-base legs (right) used in the biological adaptation lesson.

3.3. Fibonacci Sequence

Several studies have investigated the effects of understanding of pattern recognition in early mathematical learning, and have found strong implications that awareness of such structures is critical to mathematical competence with young learners.[30-33] In spite of this, pattern recognition, within perceptual learning (improvements in information extraction as a result of practice), is typically not explicitly addressed in standard math instruction.[34,35] Mulligan and Mitchelmore[33] studied the effects of training K-6 teachers in methods of instruction for pattern awareness, as well as the effects of pattern awareness instruction on low-math-achieving kindergarteners, and found improvements in student math performance following the use of the newly introduced instruction methods. Papic, Mulligan, and Mitchelmore,[30] also assessed the development of preschoolers' mathematical performance and found a strong correlation between pattern recognition and multiplicative reasoning. It has been argued that the awareness of mathematical and structural patterning is essential in mathematical learning.[30] In this case, technology, such as robotics, can allow students to visualize seemingly unrecognizable patterns, and create an opportunity to engage young students in algebraic thinking. This lesson uses the mobile robot displayed in Figure 4, to reinforce the concepts associated with mathematical sequences by introducing the Fibonacci sequence through hands-on pedagogy and collaborative group learning.

To familiarize students with mathematical sequences, they are introduced to the concepts through an oral presentation. This allows for the auditory learners to receive the content through oral representation, while simultaneously providing several opportunities throughout the lesson

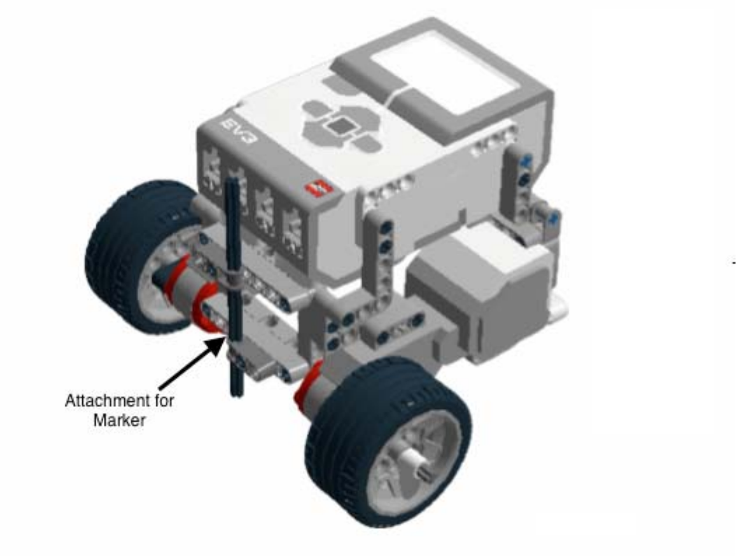

Figure 4: Mobile robot instrumented with an attachment for a marker.

for active participation. Similarly to the lesson on biological adaptation, students are encouraged to participate through inquiry-based learning. For example, by presenting students with a sequence that simply adds one unit to the previous number (0, 1, 2, 3, …), students can actively participate in counting out loud. However, more complicated sequences are not as easily illustrated through oral representation. In this case, a mobile robot presents the content through a visual representation, which provides students with a new conception.

The mobile robot is designed to drive in a path representative of the Fibonacci sequence, demonstrating how rapidly the terms of the sequence increase. As shown in Figure 5, the distance of each segment in the path that the robot is programmed to follow represents lengths equivalent to terms of the sequence. As shown in Figure 4, the mobile robot is instrumented with an attachment for a marker, which traces the path that the robot follows. Once again, for this lesson, students work in groups of three to four to construct an understanding of the Fibonacci sequence. The robot is placed in the center of a large sheet of paper, and the program is executed, producing the outline of the path on the sheet of paper. Students actively participate and relate the motion of the robot to the sequence by orally verifying which segment represents specific terms of the sequence. Ferdig[7] argues that the production of artifacts, or material objects that have been modified over the course of a lesson, such as the drawing of the path in this lesson, assists in the learning process. In this lesson, the "artifact" is used with rulers to collect measurements of the distance that the robot travels during each segment. The resulting data generated from collecting measurements allow students to verify the robot's path representing the Fibonacci sequence, and in turn, builds a deeper understanding of the content.

4. Assessment

Seemingly, the simplest way to measure the effects of a new technology introduced into the classroom would be a pre- and post-intervention assessment of the students' relevant content

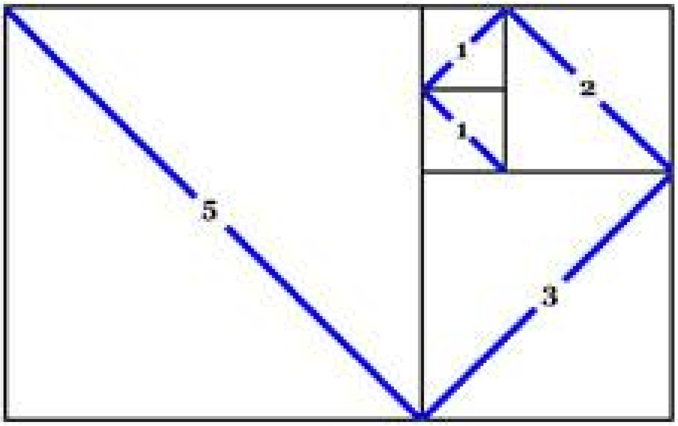

Figure 5: The outline of the path the mobile robot is programmed to follow in this lesson.

knowledge. Results would be confounded, however, by classroom factors other than the presence or absence of the new technology, which also may contribute to the pedagogical outcome. Since it is not always possible to control for these myriad other factors, Ferdig[7] suggests three criteria for evaluating the effectiveness of technologies in pedagogy: (1) appropriate uses of technologies, (2) content learning outcomes, and (3) qualitative and observational data of social and emotional outcomes.

To assess the effectiveness of robotics in the biological adaptation intervention, we combined a pre- and post-intervention assessment of content knowledge, teacher and researcher observational data on appropriate use of technology, and social and emotional responses to the technology. To successfully implement robotics under the TPACK framework, appropriate integration of technology in the classroom is essential. For this study, the teacher observing the students' behavior and pedagogical outcomes of the lesson is well-qualified to participate in this assessment because she possesses a master's degree in technology integration in K-12 classrooms. This allowed for the teacher's observations to hold significant value and it allowed effective technology integration, which is essential for success under the TPACK framework.

4.1. Pre- and Post- Assessment

To evaluate the impact of introducing robotics in the biological adaptation lesson, a pre- and post-assessment of content knowledge was administered. The students' in this study did not have previous experience with content related to biological adaptation; therefore students' pre-assessment was administered after a lecture-style presentation introducing necessary content. The description for the biological adaptation lesson, above, provides details on the material introduced to the students prior to the pre-assessment.

The results from the pre-intervention assessment suggest that the majority of students did not retain the content knowledge adequately. When simply asked to describe adaptation, several students referred to adaptation as "hiding." At first such a response may seem completely irrelevant, however further analysis indicated that this confusion may have stemmed from the discussion concerning camouflage. These students were not able to connect the relationship between camouflage and survival. However, there were multiple instances of students referring to adaptation in terms of "change" and "survival." One student responded, "adaptation is the change of someone or something to survive," which implies this student was able to retain the content knowledge from the presentation. Students were also asked what causes animals to adapt; once again, the majority of the students in the classroom were unable to provide a reasonable explanation. However, 8 out of 23 students referred to the cause for biological adaptation in terms of survival, which suggests these students' were able to develop a fundamental understanding of adaptation from the presentation. Conversely, the remainder of the class was unable to provide a response to the question that adequately demonstrated an understanding of the content. Thus, the pre-intervention assessment suggests that the majority of students in the classroom did not comprehend the fundamentals of biological adaptation.

Following the administration of pre-assessment, the students were exposed to the hands-on robotics segment of the lesson, with the intent to provide them with a new, more tangible representation of biological adaptation. The robotics portion of the lesson allowed students to visualize some factors that may engender biological adaptation. For example, the robot instrumented with the legs having the pointed-base was unable to move easily through the cotton balls compared to the robot with the wide-base feet. Students were then able to connect the relationship between survival and the ability to traverse the environment, because an animal that is unable to travel to find food cannot survive. Concerning this lesson, students were asked, "How might animals in the arctic adapt over years?" As expected, many students readily connected the larger footprint to adaptation in an arctic environment. In fact, 10 out of 23 students made this connection; a few of these responses also referred to the animal not "sinking" into the snow, which implies these students understood the reasoning behind the advantages of the larger footprint. Some students provided responses in which they applied their new knowledge to examples having nothing to do with locomotion, suggesting they had developed an even deeper understanding of the content. One student responded, "by growing more fur," suggesting this student understood the relationship between biological adaptation and needs for survival, because warmth is an essential component of survival in this type of environment. A second student answered, "by changing color," which leads back to the classroom discussion about camouflage. This student's response demonstrates a clear connection between the content introduced during the presentation and the content provided during the robotics part of the lesson. These students were able to deduce the relationship between an anatomical feature (fur thickness or color) that was not the focus of this part of the lesson, and adaptation in an arctic environment.

The responses to the pre- and post-assessment suggest that students' understanding of biological adaptation was improved through the use of robotics. The new representation provided by the robot allowed them to visualize biological adaptation in a way that traditional pedagogy does not support. The results of the post-intervention assessment suggest that students were able to comprehend the relationship between adaptations in anatomical features and survival.

4.2. Teacher and Researcher Observations

The teacher's observations of students' vocabulary use, interest level, use of the technology, and their social and emotional responses during the biological adaptation lesson suggested students understood the content represented by the mobile robot. The extent to which the students incorporated new lesson-related terms such as adaptation, survival, need, adapt, etc., contributed to the assessment of students' understanding of the content. The teacher indicated that the students were unfamiliar with the concept of biological adaptation prior to the lesson presentation. Initially, both the teacher and researcher observed that the students struggled to even pronounce the word “adaptation.” However, throughout the lesson the word was used frequently to help students become familiar with both the meaning and context in which the word is used. By the end of the robotics portion of the lesson, the teacher observed several students (who initially struggled with the word) using the word adaptation in complete sentences. One student even extrapolated from the lesson and stated, “if I had an adaptation it would be big ears so that I could hear everything better.” This demonstrated the student not only captured the meaning of adaptation but was also able to apply the meaning in a personal context.

In addition to constructing an understanding of newly introduced words, it was observed that students incorporated vocabulary learned previously into the current lesson. For example, during the presentation a few students used the term “camouflage,” when discussing the fur of a snow tiger (displayed on the projector). During the robotics part of the lesson, the researcher asked students questions that allowed them to elaborate on how camouflage may help the snow tiger stay alive. This effort forced students to evaluate how this “specialized feature” benefits the animal in terms of survival. Many students explained that camouflage allows the animal to gather food without being seen, which helps the animal survive. The researcher then used inquiry-based learning to enhance students understanding of how locomotive features contribute to an animal’s survival. For example, students were questioned on how the distance the robot (snow tiger) is able to travel through the cotton balls (snow) impacts its ability to survive. Students quickly acknowledged the advantages of the wide-base feet; they improve the “snow tiger’s” ability to rapidly travel through the cotton balls. Students were then able to relate these advantages to the animal’s ability to survive because the wide-base feet allow the animal to more efficiently traverse the environment in search of food. Students demonstrated their understanding of how specific inherited traits (camouflage through fur coloration) of an animal can provide an advantage to their survival (adaptation), thus connecting the new lesson content to content presented to them earlier.

Student interest-level plays an important role in assessing this instantiation of TPACK with robotics. During the lesson, the teacher observed that, as expected, the students were extremely interested in the walking robot; moreover, the students’ interests increased during the presentation as the researcher used the *robot-as-animal* analogy with inquiry-based learning to help them form a hypothesis about biological adaptation. In fact, the researcher also noted this increase in interest, which prompted the subsequent use of situated cognition to develop the storyline used during the robotics lesson. Specifically, the researcher’s use of the robot to represent an animal allowed students to invest interest in the survival of the animal. This heightened interest was clear as students were cheering for the robot as it walked through the snow with the second, better adapted, set of legs.

Notably, this activity readily allowed participation from all students in the classroom. Specifically, the teacher observed an equal participation from both boys and girls in the classroom. The active participation demonstrated by both genders suggests this application of robotics within the TPACK framework does not restrict or inhibit learning for either gender.[36-38]

Level of interest or engagement in STEM content varies among students, overall, and for a given student, among STEM disciplines. During this lesson, the teacher observed the students' current engagement in the STEM activity, in relation to their individual typical level of previous interest. These robotics-themed lessons were designed to provide students with the opportunity to participate regardless of their background. The teacher specifically noted that, "the technology portion of this lesson allowed students to really use this interdisciplinary approach and feel successful." This is extremely important because providing students with a sense of success instills excitement about the content and promotes engagement during the lesson, as shown.

Teacher observations of the extent to which students used the robot appropriately also contribute to our ability to assess the use of this technology as an effective pedagogical tool. Her initial observation was that some of the students viewed the robot as a "toy," rather than as an educational tool. However, once an explanation was provided to the students by the researcher regarding the purpose of the robot, students were able to generate an understanding of how the robot was being used to represent a snow tiger. In fact, by the end of the lesson, the teacher observed students referring to the robot as other types of animals as well. This demonstrated that students were able to convert their perception of the robot from a toy to an animal with specific needs for survival, as described to them in the lesson.

Social and emotional outcomes also contribute to our evaluation of the success of a technology under the TPACK framework. Ferdig's criteria support this argument, as social constructivist pedagogy is considered a characteristic of a sound technology integration.[7] In other words, students' actively participating with one another effectively promotes learning. This lesson employs collaborative-learning as students participate in shared endeavors through group discussions and data collection. Many of the students in the classroom previously demonstrated challenging behavior issues for the teacher. Interestingly, the teacher observed these students engage in the lesson, in need of few reminders to stay on task. The students also demonstrated impulse control; none of the students attempted to touch or grab the robot without permission. The ability for these 3rd grade children to demonstrate self-restraint, according to the teacher's personal knowledge of their previous behavior, further suggests that this integration of technology was successful and illustrates the potential influence robotics can have on classroom behavioral issues. The robot in this case allowed for social interactions to promote learning and mitigated behavioral outbursts.

5. Recommendation

To benefit future work, we support the criteria offered by Ferdig[7] to evaluate the validity and success of a technology integration: appropriate use of technology, content learning outcomes, and qualitative and observational data of social and emotional outcomes. These criteria provide a holistic summary of pedagogy, people, and performance for a given technology integration. For K-12 teachers interested in incorporating the above or similar lessons into their curriculum, there are a few points to note. There are several sources of funding available for teachers seeking to integrate similar robotics technology. In fact, the LEGO website provides links to applications for several grants, making this technology integration financially possible. Factors such as behavior and age must also be considered when introducing robotics into the classroom. Behavioral issues may interfere with the ability to construct certain lessons or promote group work. The LEGO Mindstorms EV3 robotics kit provides a multitude of difficulty levels for curriculum design considering both experience and age-level. For example, elementary grade students are exposed to interchanging components on the robot in the biological adaptation lesson, while middle school students are introduced to wirelessly polling sensor data in the energy lesson.

6. Conclusion

Although Shulman's[1] construct of PCK provides a foundations for teaching many types of classroom content, some topics might lend themselves to technological demonstrations more readily than others. Through appropriate technology integration we have described the methods, applications, and effectiveness of robotics technology to help students visualize three examples of typically abstract physics, biology, and math content knowledge. The lessons described in this paper demonstrate the ability of robotics to provide new and varied representations of disciplinary content in these STEM subjects. Specifically, students' difficulties with energy related concepts,[17-22] misconceptions of biological adaptation,[23] and lack of pattern recognition skills[30-33] prompted the development of these lessons.

For educators interested in creating and implementing their own robotics based lessons under the TPACK framework, the three lessons presented in this paper provide a guideline for such design. Contrary to technocentric approaches, it is recommended to first determine disciplinary classroom content that can be aided by technology integration. Next, educators can examine the robotics platform for its relevance and affordances to the lesson content. Even as the use of the LEGO robotics kit alone generates genuine interest in the subject matter from students and promotes their participation, it is critical that the robotics-based lessons provide alternative and enriched representations of disciplinary content for enhancing students' understanding.

The complete assessment of the biological adaptation lesson fully illustrated the appropriate use of technology, as well as its positive social, emotional, and behavioral impacts. The pre- and post-assessment of the lesson suggests students benefited from the robotics portion of the lesson, and were able to generate deeper understanding of the content through hands-on interactions with the robot. Students' responses to the post-intervention assessment suggest they were able to identify a link between biological adaptations and an animal's need for survival. Teacher and researcher observations during the biological adaptation lesson also support the claim that the use of robotics technology provided the teacher with an improved pedagogical tool. Students' correct use of lesson-related and integration of previously learned vocabulary suggests that they were able to retain and synthesize the content. Participation within the classroom was not observed to be gender specific, which indicates that the introduction of robotics in this lesson did not restrict learning from either gender. In fact, the active participation allowed students to generate a sense of success during the lesson, which in turn instills excitement about the subject matter. Surprisingly, many of the students who previously demonstrated challenging behavior issues were observed engaging in the lesson, needing few reminders to stay on task. In conclusion, this novel instantiation of TPACK using robotics provides a promising means to address pedagogical issues associated with teaching particularly abstract STEM related content and suggests that the TPACK framework can successfully be used as a guideline for designing unique lessons. The three lessons described in this paper offer educators immediately implementable lessons that incorporate technology integration and provide a guideline for creating new lessons.

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