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Teaching Elementary Mathematics with Educational Robotics

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Teaching Elementary Mathematics with Educational Robotics

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ABSTRACT

Current education reforms call for engaging students in learning science, technology, engineering, and mathematics (STEM) in an integrative way. This critical case study of one fourth grade teacher investigated the use of educational robots (ER) not only for teaching coding, but as an instructional support in teaching mathematical concepts. To support teachers in teaching coding in an integrative and logical manner, our team developed the Collective Argumentation Learning and Coding (CALC) approach. The CALC approach consists of three elements: choice of task, coding content, and teacher support for argumentation. After a cohort of elementary teachers completed a professional development course, we followed them into their classrooms to support and document implementation of the CALC approach. Data for this case consisted of video recordings of two lessons, a Pre-interview, and Post-interview after each lesson. Research questions included: How does an elementary teacher use the CALC approach (integrative STEM approach) to teach mathematics concepts with ER? What are the teacher's perspectives towards teaching mathematics with ER using an integrative STEM approach? Results from this critical case provide evidence that teachers can successfully integrate ER into the mathematics curriculum without losing coherence of mathematics topics and while remaining sensitive to students' needs.

Keywords: STEM Integration; Argumentation; Educational Robotics; Teacher Perspectives; Engineering Education; Coding

The calls to integrate STEM (i.e., science, technology, engineering, and mathematics) education at the elementary level have become a national priority (National Science and Technology Council, 2013). Research has shown that elementary students are capable of learning mathematics and science concepts in technology and engineering contexts, and elementary classrooms provide a powerful environment for STEM implementation and learning (Baker & Galanti, 2017; English, 2017; Estapa & Tank, 2017). The Standards for Technological and Engineering Literacy (ITEEA, 2020) support the integrated nature of STEM and advance not only authentic connections across the individual STEM areas, but also learning of each individual STEM discipline.

Some engineering and technology educators have argued that elementary STEM education provides rich opportunities for Technology and Engineering Education to thrive (Daugherty et al., 2014). The study reported here grew from a collaboration among university faculty from Engineering, Technology and Engineering Education, Mathematics Education, and Science Education. The Educational Robotics (ER) activities were provided through a Technology and Engineering Education course for elementary teachers and the argumentation and mathematics instruction was guided by a faculty member in Mathematics Education.

STEM integration requires the inclusion of two or more STEM disciplines in a manner that supports students in making connections across disciplines while at the same time ensuring that students develop conceptual knowledge within each of the disciplines (Bybee, 2010). ER has been considered an effective tool not only for teaching coding itself but for developing interest in STEM-related activities and practices (Gomoll et al., 2016). Argumentation has been recognized as an essential goal in STEM fields of education due to its support for a student's ability to rely on evidence for verification and the impact on student learning when they are actively involved in collective argumentation.

Problem Statement

Some mathematics educators and researchers (e.g., Baker & Galanti, 2017; English, 2016; Shaughnessy, 2013) have expressed concern about the role of mathematics in integrated STEM instruction; they argue mathematics is reduced to supporting calculation and representation, which are less likely to produce positive learning outcomes or authentically engage students in mathematics. In other words, from a mathematics education perspective, STEM integration "must involve significant mathematics for students" (Shaughnessy, 2013, p. 234) and should play a key role in promoting conceptual understanding of mathematics.

There is limited empirical research about ER's full potential as an instructional support in teaching mathematics content (Zhong & Xia, 2020). Although integrating ER and computer coding into mathematics instruction has been positively linked to students' understanding of mathematics concepts (Fernandes et al., 2009), mathematical dispositions (Padayachee et al., 2015), and skills development, such as computational thinking (Leonard et al., 2016), use of ER alone may not enhance mathematical learning. We propose that the choice of task, the context of learning, and support from teachers play vital roles in integrating and reinforcing the interconnections between students' mathematics learning and the use of ER (Conner et al., 2020).

In this study, we view argumentation as a bridge across disciplines in the teaching and learning of STEM (we consider computer coding to be a component of STEM). We examine the role of argumentation in teaching integrative mathematics lessons and explore the use of ER in teaching and learning mathematics concepts.

Literature Review

Argumentation

There are many benefits of incorporating argumentation in classroom discourse (Andriessen, 2006; Goos, 2004; Whitenack & Yackel, 2002). For instance, argumentation practices offer the means to focus students on the need for quality evidence, which helps to develop their deep level understanding of content (Nussbaum, 2008). Argumentation as a construct is complex and multifaceted; it may be interpreted in various ways based on different aspects of argumentation theory (van Eemeren et al., 1996). This study follows a dialectic perspective (Habermas, 1984; Toulmin, 1958/2003) toward argumentation, in which the goal of argumentation is reaching a mutually accepted conclusion about the truth of a claim. Krummheuer (1995) referred to argumentation that takes place in a social setting as *collective argumentation*. In this study, we adopted Conner et al.'s (2014) definition of collective argumentation as "any instance where students and teachers make a mathematical claim and provide evidence to support it" (p. 414).

In mathematics and science education literature, Toulmin's (1958/2003) model has been widely used to identify argument components and analyze argumentation practices (Chin & Osborne, 2010; Conner et al., 2014; Erduran et al., 2004; Jiménez-Aleixandre et al., 2000; Krummheuer, 1995, 2007; Osborne et al., 2004; Zhuang & Conner, 2018). An argument includes three core components: a *claim* (or hypothesis) that is based on *data* (or evidence) accompanied by a *warrant* (or reasoning) that relates the data to the claim (Krummheuer, 1995; Toulmin, 1958/2003). Following Conner (2008), our adaptation of Toulmin's diagrams (see Figure 1) includes the use of color and line style to record the contributor(s) of a component for a given argument and uses 'Teacher Support' to denote teachers' contributions and actions that prompt or respond to parts of arguments. Sometimes, parts of an argument may not be explicitly stated by the teacher or students but can be inferred from the context of the argument in the given classroom community; these implicit parts are labelled with a surrounding cloud.

Educational Robotics in Mathematics Teaching

A report (Seehorn et al., 2011) published by The Association for Computing Machinery (ACM) and the Computer Science Teachers Association (CSTA) outlined learning standards for K-12 computer science education and arranged these standards into levels for elementary, middle, and high school grades. This report recommends the integration of the foundational concepts of computer science (e.g., algorithmic thinking) into concepts that are currently taught in the elementary grade science, mathematics, and social studies curricula and explicitly stipulates that computer science concepts should be embedded in the middle school curriculum. Numerous studies (e.g., Grover & Pea, 2013; Lye & Koh, 2014) offered different strategies that would meet the ACM-CSTA recommendations for incorporating computer programming and other STEM studies into K-12 school activities. ER are often used to teach children how to program while they apply what they have learned in mathematics and science (Barker et al., 2014; Kazakoff et al., 2013; Liu et al., 2010). A review of the literature (e.g., Benitti, 2012; Karim et al., 2015; Mubin et al., 2013) provides evidence that teachers are hesitant to use ER to learn new concepts unless these concepts can be linked to a learning standard. Zhong and Xia (2020) investigated how ER has been incorporated into mathematics education and found in the few published studies, ER most often are linked with the learning of geometric and algebraic concepts.

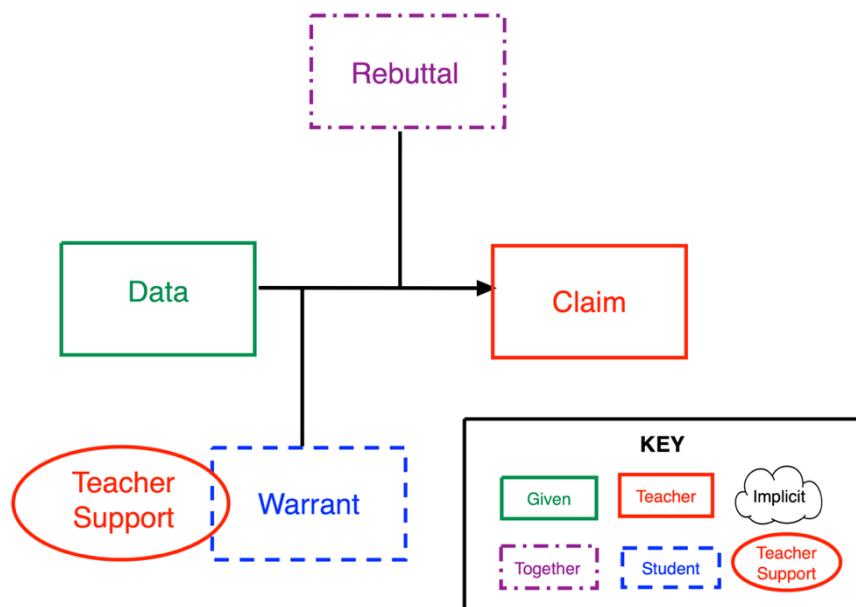


Figure 1. Components of an Expanded Toulmin's Diagram (adapted from Conner, 2008).

Teacher Perceptions of STEM Integration

Many teachers value integrating mathematics with other disciplines, but they also perceive barriers to the implementation of STEM integration (Conner et al., 2020; El-Deghaidy et al., 2017; English, 2016; Margot & Kettler, 2019). These barriers included lack of strategies to provide students opportunities to learn mathematics in integrated STEM contexts and support for teachers to incorporate engineering and technology into mathematics instruction. A literature search of studies that investigated teachers' perceptions of integrated STEM revealed mixed results. A limited number of studies focused specifically on mathematics teachers' perceptions. In their review of literature, Margot and Kettler (2019) found several factors that could impede or facilitate positive perceptions of integrated STEM: (a) years of teaching experience, (b) teacher age, (c) prior experience with STEM application and (d) school context (e.g., administrative flexibility for curricula structure, content support). The teacher's subject and the teacher's experience are other factors that predict teacher perception of integrated STEM (Al Salami et al., 2017; Shidiq & Faikhamta, 2020; Thibaut et al., 2018a, b, 2019). Teachers' perceptions of STEM integration in science and technology classrooms are more positive than their perceptions of STEM integration in mathematics classrooms; however, the relationship becomes more positive with professional development (Al Salami et al., 2017; Nadelson et al., 2013). The literature provides evidence that mathematics teachers regard STEM integration as an approach that allows students to apply mathematics in real-world situations, but recognize that STEM integration must address content standards (Thibaut et al., 2018a; Wang et al., 2011; Weber et al., 2013).

Findings from the limited research on elementary school teachers' perceptions of STEM and integrated STEM are mixed. Teachers commonly express positive views toward STEM but also express opinions that challenge the implementation of STEM integration (Lamberg & Trynadelowski, 2015; Park et al., 2016; Toma & Greca, 2018). Participants who attended an early childhood conference expressed a perspective that STEM, including STEAM, is a separate content

area for students to learn and is not integrated content learning (Jamil et al., 2018). Park et al. (2017) reported that 2/3 of interviewed elementary teachers regarded STEM education as important. Although this literature is limited, studies show that professional development programs can positively influence elementary school teachers' perspectives (e.g., Jamil et al., 2018; Laksmiwatti et al., 2020; Nadelson et al., 2013; Park et al., 2017).

Conceptual Framework

The conceptual framework for this study was the Collective Argumentation Learning and Coding (CALC) approach and model (Conner et al., 2020; see Figure 2). The CALC approach is based on a dynamic, learner-centered integrative approach to STEM (Sanders, 2012; Sanders & Wells, 2010; Wells, 2013). Integrative STEM, as implemented in CALC, encourages synchronous versus asynchronous instruction of coding, mathematics, science, and argumentation, and the use of ER presents contextualized problem-solving experiences that give purpose and meaning to mathematics and science. Traditional approaches to learning content in elementary schools have often been siloed, and time periods have been defined in lesson plans for addressing disciplines separately. The CALC approach asserts that if argumentation is a collective practice in each STEM discipline individually, then argumentation can be a unifying construct for teachers in achieving integrative STEM. The CALC approach consists of three elements: choice of task, coding content, and teacher support for argumentation.

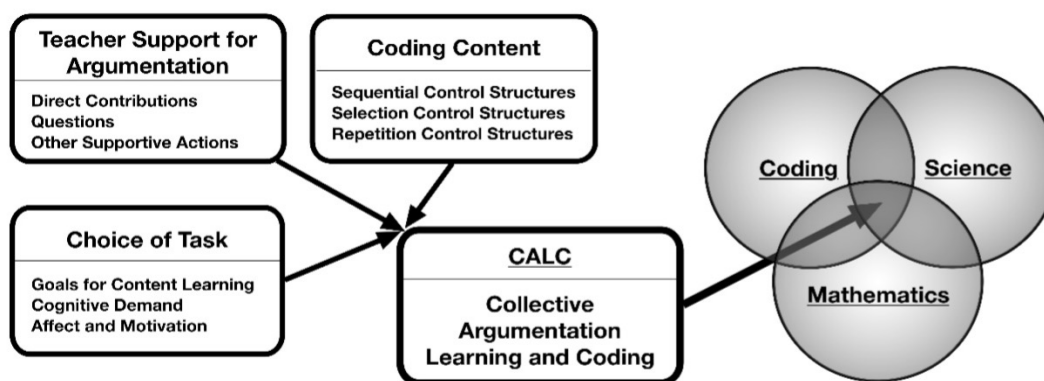


Figure 2. The CALC Framework (reprinted, with permission, from Conner et al., 2020).

Choice of Task

The element of *choice of task* in the CALC framework provides three criteria to assist teachers in selecting robotics task for integrative STEM learning. First, teachers are to shape task goals that consider conceptual understanding of mathematics, science, engineering, or technology as well as the skills students need to develop the code logically. For instance, teachers can address students' understandings of angles and angle measure while students develop pseudocode for programming an ER to travel the perimeter of a scale model of the Pentagon building in Arlington, VA. Second, teachers are to ensure integrative STEM tasks are complex enough so that students will need to reason about and discuss viable solutions to the tasks (see, e.g., Smith & Stein, 1998). Finally, teachers are to see that the task would be motivating and lead to positive affective outcomes for students.

Coding Content

The element of *coding content* focused on teachers' knowledge of algorithms, variables, use of control structures, and modularity in coding. Of significance for the current study, the CALC approach emphasizes three basic control structures that are developmentally appropriate for elementary students (K-12 Computer Science Framework, 2016): sequential, selection, and repetition. A sequential control structure executes a coding sequence line-by-line – similar to following a recipe or list of commands in order. The selection and repetition control structures are for more complex tasks. A selection control structure is suitable for tasks involving a decision before proceeding on to the next step. For instance, some cars are programmed to turn on the headlights if the lighting is not optimal for visibility. A repetition control structure executes repetitive tasks; it sometimes can make sequential control structures more efficient in terms of the number of lines of coding. For instance, instead of having five lines of codes for an ER to blink a light five times in succession, a programmer can “loop” or repeat that one line of code five times. These fundamental control structures are combined with the choice of task so that teaching and learning of STEM content is supported.

Teacher Support for Argumentation

Based on Conner et al.'s (2014) framework for teacher support of collective argumentation, the element of *teacher support for argumentation* outlines three kinds of support teachers can provide when engaging their students in argumentation: directly contributing argument components, asking a question that prompts a student to contribute, or engaging in some other supportive action that responds to a student's contribution to the argument (see Table 1). A teacher may make a direct contribution to an argument by providing a claim (e.g., The use of repetition will make the code more efficient). Teachers may ask questions that *request an idea* (e.g., So if I have eight-tenths and I doubled it, how many wholes would it fill?) or *request elaboration* (e.g., And why did you double the eight-tenths?), prompting students to contribute a claim or warrant. Teachers' other supportive actions (e.g., *repeating* a student's claim or warrant verbally or by writing it on the board) also support argumentation.

Research Questions

The following research questions guided this study: How does an elementary teacher use the CALC approach (integrative STEM approach) to teach mathematics concepts with ER? What are the teacher's perspectives towards teaching mathematics with ER using an integrative STEM approach?

A focus on teaching and learning of mathematics was chosen as a focus because it is one of the more challenging applications for ER and the CALC approach. Technology and Engineering Educators frequently find that ER has obvious connections to science content (think simple machines) or technology (electrical control systems), but effectively implementing ER to enhance learning in mathematics has implicit hurdles.

Table 1

Teacher Support for Collective Argumentation Framework (reprinted, with permission, from Conner et al., 2014)

Direct Contributions		Questions		Other Supportive Actions	
<i>Claims</i>	Statements whose validity is being established	<i>Requesting a factual answer</i>	Asks students to provide a mathematical fact	<i>Directing</i>	Actions that serve to direct the students' attention and/or the argument
<i>Data</i>	Statements provided as support for claims	<i>Requesting a method</i>	Asks students to demonstrate or describe how they did or would do something	<i>Promoting</i>	Actions that serve to promote mathematical exploration
<i>Warrants</i>	Statements that connect data with claims	<i>Requesting an idea</i>	Asks students to compare, coordinate, or generate mathematical ideas	<i>Evaluating</i>	Actions that center on the correctness of the mathematics
<i>Rebuttals</i>	Statements describing circumstances under which the warrants would not be valid	<i>Requesting elaboration</i>	Asks students to elaborate on some idea, statement, or diagram	<i>Informing</i>	Actions that provide information for the argument
<i>Qualifiers</i>	Statements describing the certainty with which a claim is made	<i>Requesting evaluation</i>	Asks students to evaluate a mathematical idea	<i>Repeating</i>	Actions that repeat what has been or is being stated
<i>Backings</i>	Usually unstated, dealing with the field in which the argument occurs				

Methods

This study is a qualitative, critical case study (Yin, 2018) of one teacher's implementation of the CALC approach. A critical case is useful to confirm, challenge, or extend a well-defined theory or approach, which in this study is the CALC approach. Therefore, we chose a critical case study design in order to examine how a teacher might implement the CALC approach in an integrative way to develop students' mathematical understandings with ER. The case was bounded by two lessons in Fall 2018 that were taught by a teacher (Sarah, pseudonym) who participated in a professional development (PD) course on the CALC approach in Spring 2018. We purposefully selected Sarah as the focus teacher because she expressed an interest in implementing the CALC approach with mathematics content and ER after participating in the PD course: "I would really like to see more of this argumentation in math...and then, how to use robots in math and how to make those connections." (Pre-Interview, 2:35). The bounded case of Sarah's two lessons provided the opportunity to confirm whether the CALC approach would engage students in STEM integration lessons that "involve[d] significant mathematics for students" (Shaughnessy, 2013, p.

234). In addition, we extend our understanding by considering Sarah's perspective towards teaching mathematics with ER in an integrative manner, about which our literature review revealed mixed results (e.g., Lamberg & Trynadowski, 2015; Park et al., 2016; Toma & Greca, 2018).

Context and Participant

The aims of the PD course were to (a) enhance teacher knowledge of collective argumentation and its application within the context of mathematics, science, and technology learning, (b) increase teachers' ability to code robots, (c) develop teachers' capacity to use collective argumentation in coding activities consistent with grade-appropriate learning content, and (d) to develop CALC-based mathematics, science, and technology lessons that could be enacted in elementary school classrooms. The course was taught in a hybrid format, with four face-to-face meetings spaced out over the course of a semester and additional instruction and assignments delivered in an online format. The PD course included 30 hours of instruction: 12 hours of instruction in face-to-face meetings and 18 hours of instruction online. After the PD course, we followed Sarah into the next school year to support and document her implementation of the CALC approach.

Sarah had more than 20 years of elementary teaching experience, most of which she described as looping with a group of students for their kindergarten and 1st grade years. Her undergraduate education background was in music performance and elementary education. She also earned a master's degree in education that emphasized integrating the arts into the general curriculum. At her school, Sarah served as a resource specialist for students who were identified as gifted; she had served for the previous three years in that role in which she described her primary work as STEM-focused. Starting in Fall 2018, Sarah began a "push-in" model, in which she co-taught gifted students with their peers with the general classroom teacher. Sarah self-selected a 4th grade class to be observed by the research team. She stated, "The class that I chose for the project is a 4th grade [class] and the time that I push into their class is math...I deliberately chose a class that had a math – it would easily work into creating some more lessons involving math, because I see that's a weakness [for me]." The mathematics class was an "advanced content" class, which means that the students were identified as either gifted or high achieving. The teachers at Sarah's school implemented the Eureka Math curriculum (Great Minds, 2015).

Data Sources

The data sources for this study included video recordings of Sarah's implementation of two fourth-grade lessons, an interview before the first lesson (Pre-Interview), and an interview after each lesson (Post1 and Post2). To video record the lessons, two cameras were placed in the classroom. One camera captured a whole-class perspective and tracked Sarah. The other camera captured the interaction of a small focus group of students. Three microphones were placed in the classroom. One microphone was worn by Sarah, one microphone was placed in the front of the classroom to capture whole-class audio, and the other microphone was placed on a table with the focus group of students. In total, there were approximately 260 minutes of video recording across the lessons.

In the interviews, Sarah reflected on the CALC approach (e.g., What would you say are the challenges in implementing the CALC approach?), her planning for the lessons (e.g., How did you

plan the lesson?), and short videos clips of her teaching (e.g., How did you support the argumentation?). The interviews ranged between 30 to 45 minutes in duration.

Data Analysis Procedures

To answer our first research question, we identified episodes of argumentation in each lesson and then selected episodes in which mathematics or coding was the primary focus of the argument. Using an adapted Toulmin (1958/2003) model (as detailed in Conner, 2008), we diagrammed the selected episodes and identified teachers' supportive actions for the arguments (Conner et al., 2014). Then, we developed a spreadsheet with a row for each argumentation diagram that described Sarah's choice of tasks and detailed mathematics and coding concepts that had been addressed within the arguments or tasks and how she supported the arguments. Using the constant comparative method (Glaser & Strauss, 1967), we searched for similarities and differences in how Sarah used the CALC approach to teach mathematics concepts with ER in the episodes of argumentation. We analyzed the potential of Sarah's task for integrative STEM instruction focused on mathematics using the CALC framework.

In order to answer the second research question, the research team met to complete a microanalysis of Sarah's interviews (Corbin & Strauss, 2015). We initially examined Sarah's interviews to understand dimensions of Sarah's experiences: implementing the CALC approach, creating lessons with ER for teaching mathematics, and interpreting students' understanding. In order to understand her perspectives more fully, we individually coded Sarah's utterances in her interviews, compared and combined our codes, looked for confirming and disconfirming evidence, and wrote memos describing themes that emerged from our iterative coding.

Results

The results of this study are presented in a narrative manner. We begin by presenting our analysis of Sarah and her orientations toward teaching, argumentation and the CALC approach, and teaching mathematics with ER. Next, we present the analysis of Sarah's first integrative lesson with ERs. We then present Sarah's task design and our task analysis for the second lesson, which sought to integrate mathematics and coding content. Finally, we conclude with our analysis of Sarah's second integrative lesson using the CALC approach.

It might be noted that the results from the first lesson provide a context for the main results in the second lesson. The lesson one data provides evidence of Sarah's thinking; the lesson two data provides evidence of learning in mathematics that took place.

Sarah's Orientation Towards Teaching

Sarah articulated views of teaching that, taken as a whole, contributed to a picture of her orientation towards student-centered instruction. Two key aspects included her emphasis on students' thinking and her role in facilitating their thinking. For example, Sarah stated, "I'm big on them thinking first, and I don't like to give them the ideas and the answers" (Pre-Interview, 13:24). A way to initiate students' thinking included asking a question: "If I know where I want to head, I would probably present more of a question to start off with, if it's a problem" (Pre-Interview, 13:24). Sarah described argumentation as the way she had always liked to teach but for which she previously didn't have a label (Post2, 16:38). She preferred for students to think and learn through argumentation rather than front-loading information (Post1, 28:01). Throughout our

conversations with her, Sarah expressed her belief that argumentation can be used in teaching any subject area (Post1, 20:25) and that argumentation is valuable for all students (Post2, 8:29).

Another aspect of her orientation towards teaching included her vision of a classroom culture in which students were not afraid to get a wrong answer: “So, with a lot of these kids, we do develop a culture of taking risks and you know being okay to get it wrong.” Post1, 22:34). She wanted students to learn from their setbacks by analyzing “what went wrong and what went right” and then decide how this analysis would allow them to “make a better choice” about how to proceed (Post1, 11:24). She related this vision of classroom culture to argumentation: “if they use argumentation and they think that through, where they make that claim and it may be wrong, but then they analyze, I think that analysis piece is critical” (Post1, 20:01). Sarah described the students’ use of feedback from ERs to identify a problem by asking, “Why didn’t this work?” (Post1, 3:52). Sarah also valued argumentation for the possibility of students hearing others’ opinions and challenging their thinking.

Sarah articulated strong views of teaching with interdisciplinary integrations. Sarah summarized this view as, “Integration is really to me, where it is [at], and that’s kind of the way that I’ve always done everything” (Pre-Interview, 28:35). Sarah’s descriptions of her planning were one manifestation of her orientation towards integration. She described including multiple content standards across disciplines in her lessons (Pre-Interview, 4:44). Sarah did not segment lessons across disciplinary lines.

Sarah’s Perceived Value of Using CALC Approach

In her pre-interview, Sarah revealed that she valued using the CALC approach in coding and ER activities and emphasized that students should use evidence to support their claims. Prior to teaching her first integrative lesson, she voiced her intention to use argumentation. Sarah wanted her students to “make some claims as to what type of code sequence would be the best for that, and why; where they could support their argument.” (Pre-Interview, 23:10). Sarah specifically noted the utility of CALC approach:

What would be done if you weren't using the CALC approach is... I think it would be... more teacher centered, in the sense of, there's not inquiry where they find out. And I think kids, too, will be less engaged, because they don't take ownership of it. (Pre-Interview, 24:23).

Sarah expressed these perspectives about the CALC approach and argumentation across all three interviews.

Sarah’s Orientation Towards Using ER to Teach Integrative Math Lessons

Sarah held a positive view towards planning for integrative STEM lessons. Her view of STEM integration included her love of “something that allows kids to connect multiple content standards together at once” (Pre-Interview, 4:44). “It’s okay if using the robots doesn’t teach new content but that it takes the content that they’ve learned and then applies it in different ways” (Pre-Interview, 9:55). Sarah thought that it made a lot of sense to teach coding and math in similar ways, “There’s so many ways to do [math]. And it’s the same way with coding is that, there’s a lot of ways to get there, but which way is the most efficient?” (Pre-Interview, 16:10). Sarah’s view of integrative STEM appeared well established, perhaps due to her already strong orientation towards integration.

Sarah consistently expressed a desire for rigorous mathematics instruction focused on conceptual understanding, and she hoped ER would provide opportunities for her students to be challenged. When Sarah talked about integrating ER, she focused on making sure that mathematics was “up to the caliber and level that those kids need” (Pre-Interview, 5:18). We interpreted Sarah’s concern for the “caliber” and “rigor” of the mathematics as engaging the students in conceptually rich mathematics that deepened their understanding and challenged them to conceive or apply mathematics in new ways. Sarah said she was “really trying to figure out how we can...really use robotics to raise that level of rigor of understanding of mathematics” (Post1, 4:42). Similarly, she concluded after the second class that engaging students in learning mathematics with ER increased engagement and “was even more challenging” for students (Post2, 5:50). When Sarah talked about her instructional goals, she inevitably talked about engaging in cross-disciplinary investigation and developing conceptual understanding.

Sarah’s Lesson 1: Using ER and CALC to Disconfirm Students’ Mathematical Understanding

An Illustrative Collective Argumentation Episode from Lesson 1

This Lesson 1 Episode is illustrative of Sarah’s first integrative lesson using the CALC approach. In the lesson, students were asked to program the ER to go 6 inches and observe how many seconds it took the ER to go that distance. The goal of this task was for students to then use proportional reasoning to decide how long the ER should travel for distances of 12 and 24 inches, without having to resort to trial and error. Lesson 1 Episode was chosen because it reflects the nature of using ER to disconfirm students’ mathematical understanding. Moreover, this episode reveals through engaging her students in argumentation, Sarah became aware that some students had not previously worked with decimal numbers, which is a fourth-grade Common Core State Standard (National Governors Association Center for Best Practices & Council of Chief State School Officers, 2010). This awareness provided Sarah with the opportunity to address mathematical content with ER in the next lesson.

In the lesson, Sarah intentionally engaged her students in argumentation; she expected students would use evidence-based reasoning to plan coding sequences for moving the ER. In the following transcript, the students had been working on coding an ER to travel 6 inches in a straight line. This Lesson 1 Episode is an excerpt from a whole class discussion in which Sarah asked a group to share their work with the class (see Figure 3 for a visual depiction).

1. S(tudent)1: Oh, no, we did two [second delay] at first and then that went 12 inches.
(Data/Claim 2) And then we did one [second delay] and that went like 7 inches.
(Data/Claim 3) And then we tried 0.5 [second delay] and that went halfway. (Data/Claim 4) And then we tried 0.10 [spoken as zero point ten], and that was only like this much [holds up fingers to show tiny amount] because that's one-tenth. (Data/Claim 5)
2. Sarah: So, tell me your order. You tried 2, then 1, then 0.5...(Support 1)
3. S1: And then 0.10 [spoken as point one zero] (Data/Claim 5)
4. Sarah: And so, when you were at 0.10, what did that get you, what results did that get you? (Support 2)
5. S1: It only got us like that much [gestures again]. (Data/Claim 5)
6. Sarah: So, you went from 0.5, which was 0.5 too far? (Support 3)
7. S1: No, it was too short. (Warrant 1)
8. Sarah: So, why did you go from 0.5, if it was too short, to 0.1? (Support 4)

9. S1: Because we didn't know that 0.1 would be that. We thought it would be more that 0.5 because it was ten. (*Warrant 1*)
10. Classroom teacher: We haven't learned fraction comparisons yet so, they were just seeing 10 bigger than 5.
11. Sarah: So, then what did you do to adjust, once you realized 0.1 is actually shorter than 0.5, what did you do? (*Support 5*)
12. S1: Then we [did] 0.9 (*Claim 6*) because that is nine one-tenths. (*Warrant 2*)
13. Sarah: Nine-tenths. (*Support 6*)
14. S1: Yeah nine-tenths. And then that would get us more farther than the 0.10. And we tried that and it was like that close [gestures an even tinier amount]. (*Warrant 2*)

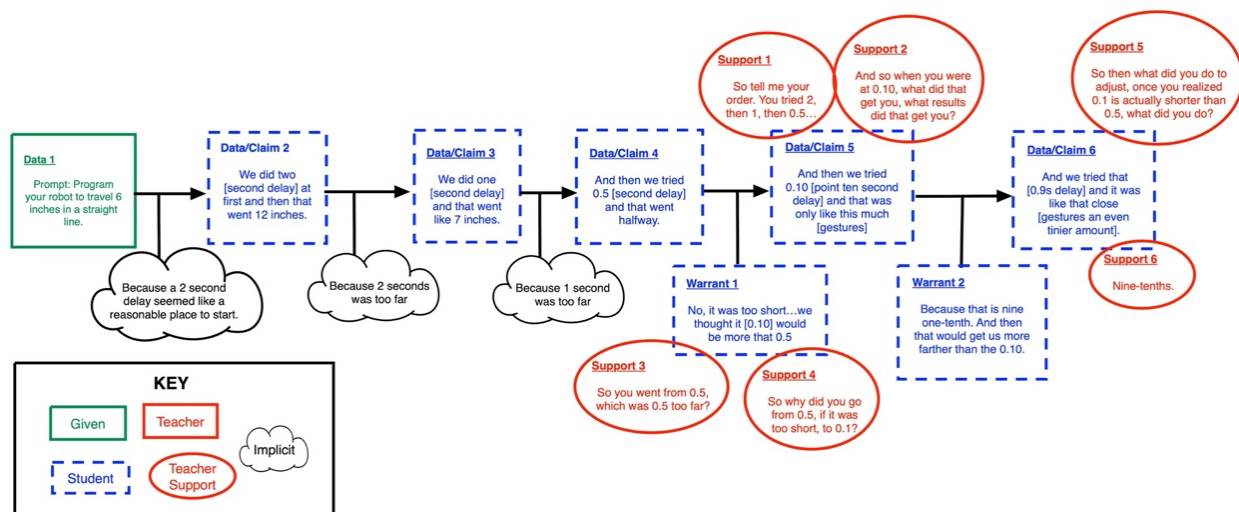


Figure 3. Lesson 1 Episode: An Illustrative Episode of Argumentation from Sarah's Lesson 1.

Sarah supported argumentation in this episode by asking questions that *requested elaboration* and *requested a method*. She ensured others in the class heard and understood students' answers by *repeating* some answers. After the group shared their work (line 1), instead of giving direct feedback, Sarah posed a question, "So, why did you go from 0.5, if it was too short to 0.1" (Line 8, Support 4) to request elaboration to uncover the reasoning for S1's claim (Data/Claim 5). The student explained, "Because we didn't know that 0.1 would be that [short of a distance]. We thought it would more than 0.5 because it was ten." (Line 9). The classroom teacher further explained to Sarah that "We haven't learned fraction comparisons yet so, they [students] were just seeing 10 bigger than 5" (Line 10). Sarah then realized that the students were still developing their understandings of decimal place value.

In summary, the use of ER in this episode provided opportunity for students to begin making sense of decimal place value. For some students, the observation that ER traveled "smaller distance" in "bigger numbers" disconfirmed their assertion that 0.10 would be more than 0.5. For Sarah, the student's arguments allowed her to assess her students as not yet knowing an important mathematical concept needed for developing their coding sequences. With this new

awareness, Sarah planned for continued learning with decimal place value in the next integrative mathematics lesson.

Sarah's Reflection on Lesson 1

After watching a video clip of the Lesson 1 Episode, Sarah explained that this episode demonstrated some gaps in students' decimal place value understanding that hindered students' completion of the task. She stated, "They went ahead and figured, adjusted based on just that alone, but they don't understand it mathematically, you know" (Post1, 17:47). We interpreted this statement as Sarah attributing students' difficulties with adjusting a coding sequence to their limited knowledge of mathematical ideas. While the students appeared to be using trial and error to successfully complete the task in the Lesson 1 Episode, Sarah believed students were systematic in their trials and there was potential for evidence-based reasoning. She also asserted that the mathematical content with which they struggled was "content that they have not encountered yet in their typical pacing of their math" (Post1, 1:52). This observation impacted her design and implementation of the second lesson we observed.

Sarah reflected that having students analyze their work from the perspective of argumentation was critical. She stated, "if they use argumentation and they think that through, where they make that claim and it may be wrong, but then they analyze, I think that analysis piece is critical" (Post1, 20:01). We interpreted this comment and others like it as indications that she perceived the CALC approach, and particularly argumentation, as shifting students away from a trial-and-error approach to coding ER and helping develop students' reasoning skills. Nevertheless, Sarah did find some value in the use of trial and error, but only when used systematically. The following statement from Sarah supports this interpretation: "Give it a shot, but then again, see what happens, think about what happened and then try to narrow your focus on so that you're not just shooting in the dark all the time." (Post1, 21:59).

Sarah's Lesson 2: Using ER and CALC to Support Students' Conceptual Understanding of Decimals

Sarah's Design of Lesson 2

Sarah was determined to recognize and build upon students' mathematical reasoning in designing future integrative mathematics activities. After reflecting on what her students said and did, related to the relationship between 0.5 and 0.10, she said, "I want [students] to have some actual practice and conceptually understand why that [0.10] actually is a smaller amount than point five" (Post1, 2:38) and "I need to develop some lessons that kind of address that...I want to make sure we have that understanding before they move forward" (Post1, 3:52).

In Sarah's second integrative mathematics lesson, her goals were for students to be able to: (a) identify equivalent mathematical representations for certain tenth areas of decimal squares (e.g., six-tenths of the area of a square in either Figure 4a or Figure 4b) and (b) develop a coding sequence for an ER to travel around those areas using repetition structures (i.e., loops). In addition to her focus on conceptual understanding of mathematical ideas, Sarah considered mathematical representations, ER platforms, and intentional scaffolding in her lesson planning.

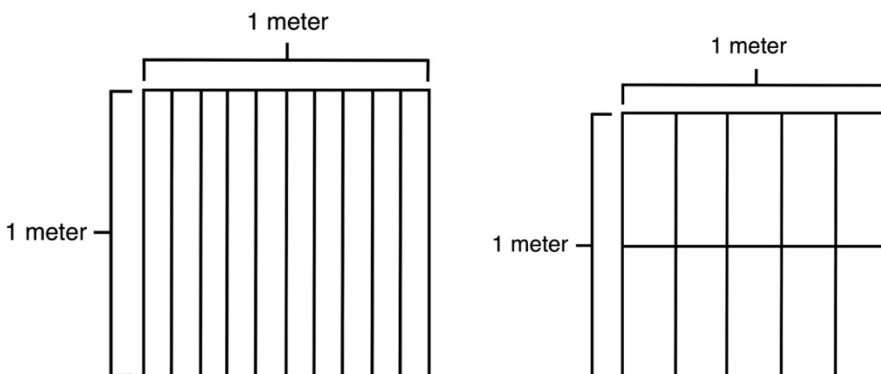


Figure 4. Decimal Square Models.

The Task Designed by Sarah for Each Group

Sarah constructed decimal squares of two different configurations on the floor of her classroom using tape (see Figure 4). Each square measured 1 meter on a side. Students, in groups, were given one of the taped squares and asked to program their robots to travel around a fractional part of the area of the square. Groups were given a decimal quantity (either 0.6 or 0.8, depending on the group) and a task page containing instructions and a sentence frame (see Figure 5). Each task page also included one of the two decimal square models illustrated in Figure 4. During the work session, Sarah interacted with groups and asked them to recount their experiences. She also pushed them to make their code more efficient. One of these interactions is captured in included Lesson 2 Episode.

<p>Your team must maneuver around a fraction of a square meter. Use the space below to record your coding successes and failures to help determine your 'next steps'.</p>	
<p>Claims (Based on results, what do you expect to be a reasonable 'next step'?)</p> <p>"If ____ resulted in ____, then ____ should result in ____."</p>	<p>Data and reasoning</p>

Figure 5. Recreation of Task Page Sarah Created to Scaffold her Students' Arguments and Coding.

Task Analysis Using the CALC Framework

We examined Sarah's task using the CALC Framework to understand its potential for supporting students' integrative STEM learning in the context of mathematics and coding. Because Sarah's goals aligned with those of the CALC project, it is not surprising that Sarah's task aligned with the CALC framework. For this task analysis, we considered Sarah's written task, her instructions to students, her account of planning the lesson, and her reflection on the lesson. Our analysis includes aspects of all three components of the CALC Framework, with the choice of task element being most salient.

The intentional scaffolding on the task page, as illustrated in Figure 5, provides evidence of attention to supporting her students' construction of arguments, including the vocabulary she chose to use of claims, data, and reasoning (*Teacher Support for Argumentation* component). Her design of the task, including intentional choice of which ER platform to use, demonstrates attention to *Coding Content*. In particular, she chose to use a platform with which her students were familiar in order to facilitate attention to the mathematics content and in hopes of her students engaging in more complex coding, including attention to loops, a repetition control structure. When asked about her goals, she said, "I was hoping that they would eventually then go into this whole idea of looping" (Post2, 4:34). We next discuss elements of the *Choice of Task* component in her task design.

Goals for Content Learning. As demonstrated above, Sarah designed her task explicitly to enhance students' conceptual understanding of decimal place value. Her goals for students included connecting different representations of fractional area. Connections are an important part of conceptual understanding as defined by Hiebert and Carpenter (1992); moving flexibly among representations is necessary for understanding fractions, including decimal fractions (e.g., Deliyianni et al., 2016; Lamon, 2001). The task provided students with opportunities to identify mathematical structures and discuss how to make their coding sequences more efficient by connecting the mathematical structures with repetition control structures. For instance, they could identify how long it took for the ER to travel $1/10$ of the length of the square and use that time and a loop to code it to travel any multiple of $1/10$ of the length of the square. They also could leverage equivalent representations of fractional areas to create more efficient codes. For instance, students could first find two or more representations in a square model that have the same fractional value. Then, given these equivalent fractional representations, students can select the representation that has fewer turns. This potential is illustrated in our account of the Lesson 2 Episode in the next section.

Cognitive Demand. The cognitive demand of a task should be appropriate for the students for whom it is designed. We consider cognitive demand to include the extent to which a task engages students in thinking, reasoning, and problem solving (Smith & Stein, 1998). Sarah gave explicit attention to cognitive demand by her intention that the task be appropriately challenging for her students. She wanted to "make it something that would be really challenging for those kids" (Pre, 20:22). Sarah's task had a high level of cognitive demand because it required them to make use of their developing understandings of decimal place value in programming ER to accomplish a task. They did not have access to a rote procedure for such activity. Additionally, they had to choose and coordinate different representations of fractional areas to make decisions about efficient programming and then explain and justify their choices to their group members and on their task pages. These aspects of multiple representations, connections, explanations, using knowledge, and complex thinking align with Smith and Stein's (1998) description of high cognitive demand tasks.

Affect and Motivation. Many students find coding ER to be inherently motivating (Chin et al., 2014). Sarah intentionally leveraged this motivation in her design of the task.

I think the engagement level —You know, if you just give some kid a problem, like on paper, and then they have to figure out what that would be, to me, they would probably do it, again, because a lot of kids would do it. But their determination to solve that problem wouldn't be as great, because to me, they're not as engaged. But then also, there's not a lot

of challenge in that, whereas what they were doing here, to me, was even more challenging.
(Post2, 5:50)

Sarah provided an appropriate level of challenge along with instructional scaffolds (the task page), and the ER provided immediate feedback regarding students' progress with the task.

An Illustrative Collective Argumentation Episode from Lesson 2

The following argumentation episode from Sarah's second lesson (Lesson 2 Episode) was chosen because it reflected how two lesson goals mutually informed each other. In the Lesson 2 Episode, Sarah provided a group of students with an additional task to code the ER in a more efficient manner. To support the goal of coding efficiency, Sarah engaged the group in argumentation related to programming the ER to travel around the same fractional part of the square with a path that involved fewer turns. By doing this, Sarah supported students to work with equivalent mathematical representations of fractions, which was one of her goals.

1. S(tudent)2: But we are trying to make it like - from here and then turning right and then go one. If I [am] measuring it, we got 6. (*Claim 1*; see Figure 6a for student's gestured path)
2. Sarah: Right, well. How? Yeah.
3. S2: What we need to do is we can go like this or we can just go
4. Sarah: What's another one you can do 6 [tenths] a little more efficiently? What is a way that you could do it that would involve fewer turns? Because if I do it this way, I've got to go here, I got to turn, I got to go up there, I got to turn, got to go there, turn, here, turn, here, turn, here, right? That's an awful lot of turns. (*Rebuttal/Data 2*)
5. S1: Really?
6. Sarah: Yeah, you got to go all the way around it. (*Rebuttal/Data 2*)
7. S1: And then back?
8. Sarah: Yes! (*Rebuttal/Data 2*)
9. S1: Okay, then we have to...
10. Sarah: So, what would be a better way to do it, that you could still do six, but with fewer turns? Look and see. Look at this. (*Support 1*)
11. S1: I think that we could go 1, 2, 3, 4, 5... (*Claim 2*)
12. Sarah: What do you think we could do? (*Support 2*)
13. S1: And then go another one that's invisible...(Claim 2, see Figure 6b for student's gestured path)
14. Sarah: There's no invisible (laughs) (*Rebuttal 1*)
15. S1: I know, I know.
16. Sarah: S2 had an "ah ha". What do you think S2? (*Support 3*)
17. S2: We could go these three right here, then turn that way, and turn that way, and then go back. (*Data/Claim 3*; see Figure 6c for student's gestured path)
18. S1: I agree.
19. Sarah: Do you see how then that would only be here, turn, here, turn, here, turn, here? (*Support 4*)
20. S1: Yeah. (*Warrant 1*)
21. Sarah: Is it still six tenths? (*Support 5*)
22. S1: Yes! (*Warrant/Claim 4*)
23. S1: Because three and three is six. (*Warrant 2*)
24. Sarah: That was good guys. That was a good thing to try to figure out. (*Support 6*)
25. S1: So two, four, six. (*Warrant 3*)

At the beginning of Lesson 2 Episode, S2 made a claim about how to program the ER to travel around six-tenths of the area in a unit square (Line 1). As shown in Figure 6a, this travel path of ER involved six turns. Instead of ending the task with S2's claim (which was technically valid), Sarah challenged students to think about "What's another one [way] you can do 6 [tenths] a little more efficiently?" (Line 4). Thus, Sarah led the argumentative discourse to concentrate on how to code the ER in a more concise way that involved fewer turns. At this point, the role of the teacher's intervention was critical to encourage students to explore how to efficiently code ER and investigate equivalent representations for six-tenths.

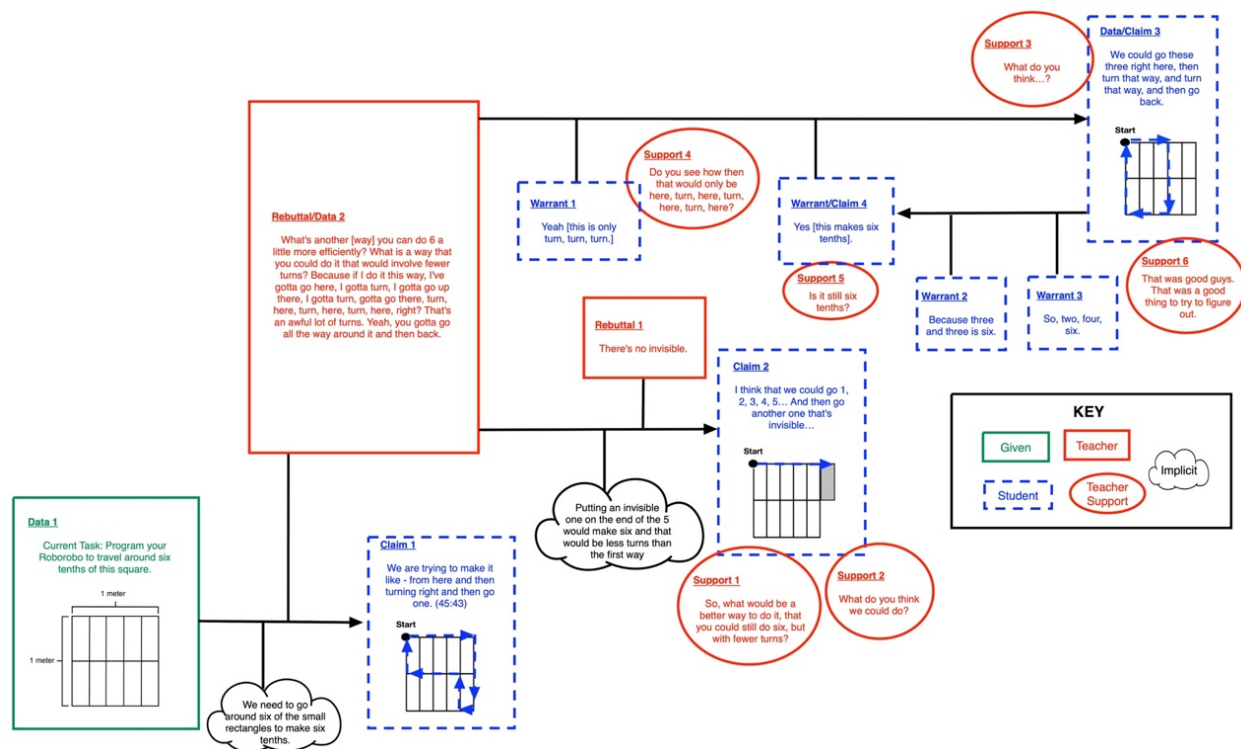


Figure 6. Lesson 2 Episode: An Illustrative Episode of Argumentation from Sarah's Lesson 2.

Another student proposed that the addition of an invisible one-tenth at the end of the five-tenths would make six-tenths (Lines 12 and 14; see Figure 7b) and would have fewer turns than the initial travel path (Figure 7a). Sarah noticed that the student's answer neglected the unit of specifically outlined square that the students were given, although it had fewer turns. Sarah contributed a rebuttal, "There's no invisible" (Line 15) in response to the student's proposal. Sarah's rebuttal not only provided students with opportunities to leverage the concept of unit and equivalent representations but also ensured that the argumentation continually progressed in a productive direction towards her goal for the lesson. The students ultimately arrived at an alternative correct travel path with explanations of how they could program the ER to travel six-tenths of the area of a unit square with only four turns involved (Lines 18 to 25; see Figure 7c). Through this process, the students determined multiple ways they could code ER to travel around six-tenths of the area in the square.

In summary, the discussion of coding efficiency in this episode required students to think conceptually about the equivalent mathematical representations of a particular fractional area. Students were expected to identify the area of six-tenth in a decimal square in multiple ways. On

the other hand, the equivalent mathematical structures provided opportunities for students to explore a more efficient path in programming an ER with fewer turns.

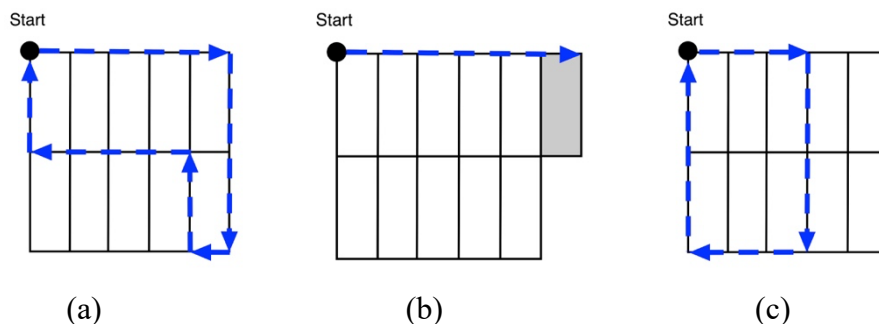


Figure 7. Student Solutions to the Task in the Second Lesson.

Discussion

While the potential benefits of incorporating ER as an educational tool are widely accepted, previous studies have mainly focused on the use of ER in teaching concepts that relate to the robotics field (e.g., programming, construction, mechatronics) and not to the teaching of mathematics (Mitnik et al., 2009; Zhong & Xia, 2020). In addition, some researchers have argued the passive role of mathematics in integrated STEM instruction (English, 2017; Shaughnessy, 2013). This study responds to calls to explore more ways for integrating ER and mathematics education (e.g., Benitti 2012; Zhong & Xia, 2020). Sarah's case provides empirical evidence to support the potential of ER in teaching mathematics concepts of decimals and fractions. The study also illustrates how mathematics could play a major role in improving integrative STEM instruction that facilitates students' in-depth conceptual understanding of mathematics as well as concepts from other STEM disciplines (i.e., coding concepts). In this section, we discuss the results of our analysis of Sarah's use of the CALC approach and her perspectives towards teaching mathematics with ER.

Use of the CALC Approach to Teach Mathematics Concepts with ER

Our results showed that Sarah's lessons aligned with the CALC approach in the following ways: (a) choice of task, (b) coding content, and (c) teacher support for argumentation. Next, we discuss each of these components.

Sarah's Choice of Task

We interpret Sarah's lessons as satisfying all three criteria of task selection as described in the CALC approach. In the first lesson, Sarah's task (and her support for argumentation) allowed her to identify a gap in students' mathematical understanding. In order to ensure students grasped the mathematics concepts of decimal place value, which they had not yet learned, Sarah shaped the task in the second lesson to address students' mathematical understandings of decimals and fractions before moving forward with coding (criterion 1). Sarah provided additional tasks so that students could determine how to code ER more efficiently by asking the students to provide

reason and discuss various paths to programming ER travel around a particular fractional area (criterion 2). In this way, the tasks that Sarah designed scaffolded the students to build knowledge in both mathematics concepts and coding structures. Furthermore, Sarah viewed the task as directly motivating for students, in particular the use of ER to engage students in coding activities (criterion 3).

Coding Content

The coding content in Sarah's lessons included sequential and repetition control coding structures. Sarah expected the students to use proportional reasoning rather than only trial-and-error to justify their block-based coding sequences. For instance, students were learning to construct a line-by-line coding sequence for programming an ER to travel 6 inches based on their previous trials. In the second lesson, Sarah intentionally extended students' exploration of coding to include repetition structures (i.e., loops) to find an alternative path of travel around the decimal square. The coding content element in Sarah's lessons focused on providing students with knowledge of and insights into control structures, which worked in combination with her strategic choices of tasks.

Sarah's Support for Argumentation

Based on Conner et al.'s (2014) framework for teacher support of collective argumentation, Sarah engaged students in participating argumentation through multiple ways. Sarah posed questions to request elaboration to elicit students' ideas and uncover their processes of reasoning (e.g., "So why did you go from 0.5, if it was too short, to 0.1?"). Sometimes, Sarah directly contributed argument components (e.g., rebuttal/data shown in Figure 6) to ensure that argumentative practices remained productive. In other instances, Sarah engaged in other supportive actions (e.g., repeating students' statements). Sarah's support for argumentation was essential for the purpose of guiding students to construct, explain, or clarify their arguments, and, in the first lesson, assisted in identifying needed conceptual understanding.

Sarah's Perspectives Towards Teaching Mathematics with ER

Sarah's perspectives towards teaching mathematics with ER using the CALC approach were consistent across time and settings. We argue that this consistency was largely due to Sarah's orientations toward teaching in general. Her orientations toward teaching were the basis for her perspectives towards teaching integrative mathematics with ER. These orientations included her value of student-centered instruction, desire for a classroom culture in which students were not afraid to be wrong, and preference for integrating content areas.

Sarah valued instruction that was student-centered, which aligns with the stance of integrative STEM (Sanders, 2012; Sanders & Wells, 2010) in the CALC approach. Sarah found the CALC approach to be consistent with her orientation towards student-centered instruction because this approach allowed students to own their claims. Sarah expressed the belief that individuals can construct their knowledge by engaging in argumentation.

Sarah believed, particularly for the advanced content students, that it was important for students to know that they could be wrong. Sarah observed that having students analyze their work from the perspective of argumentation was critical. With the CALC approach, challenges to students' problematic claims did not lead to unproductive discourse but led to civil discussions

about ideas and concepts that supported the classroom community. This aligns with goals for argumentation across disciplines (Andriessen, 2006).

Sarah also valued integration in her instruction. Her previous graduate studies focused on how to integrate the arts across the general curriculum. She described this integrated approach to teaching as working well for her and that she generally regarded her teaching as integrative. For instance, she described how her lesson plans often connected multiple content standards across disciplines. The CALC approach aligned with Sarah's orientation towards integrating content across disciplines in order to meet learning goals for the students. For Sarah, using the CALC approach did not take away from developing rigorous mathematics with students. Rather, Sarah found that she could integrate mathematics with ER in ways that challenged students, while also engaging them in meaningful learning of mathematics.

Limitations

In suggesting that elementary teachers can integrate ER to teach formal mathematical and coding concepts, we also recognize the limitations of this critical case study. We examined two lessons focused on one mathematical concept from one teacher, including a pre-interview and post-lesson interview for each lesson. Although we cannot claim that the findings will generalize to other mathematical concepts or are reflective of elementary teachers' capacities to teach mathematics with the CALC approach, we believe the findings are generative for preparing teachers to teach STEM in an integrative manner.

Conclusion

This critical case study afforded the opportunity to strategically investigate if the conceptual model of the CALC approach could support teachers using integrative STEM. Sarah was an ideal candidate to build our critical case because her initial perspectives aligned with the goals of CALC and integrative STEM, in general. She was well-poised to implement the CALC approach into her practice because she had participated in previous long-term PDs with some of the university faculty. Sarah's participation led to partnerships that built mutual trust and her goal for integration. This critical case reveals what is possible in teaching integrative STEM lessons using argumentation. We recognize future studies with other teachers that participated in the PD course may contribute to building more encompassing theory for CALC. Nevertheless, this critical case of Sarah's lessons provides some cogency to the CALC approach.

Sarah's critical case shows that ER combined with the CALC approach can be used to teach mathematics concepts in ways that are consistent with an integrative STEM perspective. We believe that Sarah's use of the CALC approach enabled her to identify students' understanding of decimals and to plan for future mathematics instruction with ER. Sarah's case also provides evidence that teachers can integrate ER into the mathematics curriculum without losing coherence of mathematics topics and while remaining sensitive to students' needs. Opportunities to reflect on her teaching with the CALC approach provided Sarah with expanded perspectives on integrating mathematics with ER. Sarah's case provides evidence of a teacher using ER and coding to effectively teach mathematical concepts. This evidence influenced Sarah's perspectives towards teaching mathematics with ER and also provided the researchers with insights into the potential for integrative STEM to be used in mathematics instruction. Future research is needed to examine

what mathematics concepts are able to be taught using integrative STEM and at what grade levels it is appropriate. Additionally, research is needed to understand how to support teachers who are new to argumentation in professional learning about integrative STEM teaching.

For Technology and Engineering educators, this study provides a model for reaching out to colleagues in the discipline of mathematics. The perspective that the role of mathematics in integrated STEM instruction is often supporting calculation and representation, which are less likely to produce positive mathematical learning outcomes (Baker & Galanti, 2017; English, 2016; Shaughnessy, 2013). We believe such perspective discourages involvement and collaboration of mathematics in integrative STEM ventures. Demonstrating the potential for true learning of mathematics concepts was a significant milestone for this study.

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