How Co-Designing Computational Modeling Activities Helped Teachers Implement Responsive Teaching Strategies

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ABSTRACT

In recent years, science education has shifted focus, from content to practice. This is reflected in the NGSS, which advocate learning science concepts through engagement in science and engineering practices. Theory building is a central activity of science and computational modeling is a key practice through which contemporary scientists construct theory. In this paper, we discuss an 8th grade science teacher's implementation of a computational modeling lesson. The teacher had co-designed the computational modeling microworld and lesson with the research team over the preceding summers. We investigate the teacher's activity during a whole-class discussion near the end of the lesson, to understand her responsive teaching strategies and how the co-designed technology supported her in eliciting and responding to student ideas. We examine the transcript from a follow-up interview to understand her experience implementing the co-designed technology and responsive teaching strategies, and to identify foci of future co-design iterations.

CCS CONCEPTS

• **Education**; • **Human-centered computing**; • **Human-computer interaction (HCI)**;

KEYWORDS

Teacher-researcher co-design, Responsive teaching, Computational modeling microworlds, Middle school science

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1 INTRODUCTION

In recent years, science education has seen a shift in focus, from content to practice [1, 2]. This is reflected in the Next Generation Science Standards (NGSS), which advocate the learning of science concepts through engagement in science and engineering practices [3]. Theory building is a central activity of science. Theory building is defined here as a family of practices, through which individuals generate, evaluate, and refine theoretical knowledge artifacts, including laws, models, explanations, and construct definitions. Computational modeling is a key practice through which contemporary scientists construct theory [4, 5]. Science teachers should therefore create meaningful opportunities for students to construct scientific knowledge through computational modeling practices.

1.1 Computational modeling instruction

Many science education research programs have designed computational modeling environments and investigated the learning they afford. There is a long tradition of asking students to create models of phenomena from Newtonian physics. diSessa [7] describes a case where high school students re-invented F=ma through their development of computational models. Sherin [8] looked broadly at the possibility of using programming as a language for expressing simple physical ideas. Wilensky and colleagues have investigated student construction of models of complex systems phenomena such as predator-prey dynamics, using the NetLogo computational modeling environment [9–11]. Recent work in this tradition has examined student construction of models using NetTango [12–14], a block-based interface to NetLogo. These studies have examined students' development of both scientific understanding and computational thinking through their construction of models [15–18].

1.2 Pursuing student thinking

Many of the computational modeling approaches described above are constructivist, as building and debugging models gives students a chance to articulate, evaluate, and refine their thinking. As such, teachers facilitating computational modeling activities are often pulled into enacting responsive teaching strategies, a family of teaching strategies that pursue student thinking. Based on the assumption that students have a wealth of productive prior knowledge with which to construct new knowledge [19], a responsive teacher seeks to 1) understand the substance of student ideas, 2) identify connections between student ideas and the knowledge and practices of the discipline, and 3) adjust instruction in order to pursue student ideas [20]. Research on responsive teaching has found that it can help develop conceptual understanding [21], engage students in disciplinary practices [22], promote student agency [23], and foster equitable participation [24]. Taking a responsive approach is beneficial, yet it presents the teacher with certain "instructional tensions" [25] or "dilemmas of practice" [26]. A primary dilemma is the general tension between achieving content objectives and allowing students to follow their own thinking and develop knowledge in a more organic way.

1.3 Exploring one teacher's engagement in responsive teaching

Responsive teaching can be a powerful approach, with research pointing to many benefits. Computational modeling provides a natural structure for engaging in responsive teaching, as it fosters students' articulation and evaluation of ideas. As noted above, however, responsive teaching presents teachers with practical dilemmas, which can make the approach daunting. Added to these dilemmas are challenges teachers face when integrating computational activities into their classrooms, including inadequate preparation [27, 28] and low self-confidence and self-efficacy [29, 30]. Given these challenges, we used a co-design approach to ground ourselves in the needs and realities of teachers, while working towards the development of technology and activities meant to support teachers' engagement in responsive teaching practices [31]. In this paper, we investigate one teacher's implementation of and experience with responsive teaching in the context of a computational modeling lesson she had co-designed with our research team. In particular, we analyze the teacher's activity during a whole-class discussion near the end of the lesson, making the focus of our inquiry the ways she engaged in responsive teaching and how the co-designed technology supported her in eliciting and responding to student ideas. We examine the transcript from a follow-up interview to understand her experience with implementing the co-designed technology and responsive teaching strategies and to identify foci of future co-design iterations.

2 THEORETICAL FOUNDATIONS

The design of theory-building instruction was based on a theory of knowledge and learning called *knowledge in pieces* (KiP) [32]. KiP is a cognitive theory of learning, which views knowledge as a complex system of elements. The elements can be thought of as nodes, which collect in networks in response to sense-making demands of a given problem or context. Novices form networks inconsistently across contexts for which experts would draw on the same knowledge. The process of transition from novice to expert is viewed as a gradual "tuning to expertise" through which the knowledge networks are reorganized and refined over time in response to feedback from the environment. The elements of the novice system are repurposed in the expert system and are therefore viewed as *resources* for the development of expertise [33]. In this way, KiP is constructivist [34]. This "resource" view of prior knowledge puts KiP into contrast with "misconceptions" views, which treat prior knowledge as a hindrance to learning, which must be identified and replaced with correct ideas [35, 36].

The role of instruction, from the KiP perspective, is to help students articulate and refine their thinking. KiP pedagogy attends to the content of student thinking, creating space for students to share their ideas and consider the ideas of their peers. KiP pedagogy therefore fits into the larger family of responsive teaching approaches discussed earlier. Theory building provides a natural activity structure for engaging in responsive teaching. Theory building encourages students to articulate their initial thinking when they generate their theoretical knowledge artifacts (e.g., models, explanations, etc.). They are asked to evaluate and refine their artifacts, which causes them to carefully examine and refine their thinking. Theory-building instruction aligns well with constructionism [37], a pedagogical theory that posits learning happens best through the construction and refinement of publicly shareable artifacts.

3 METHOD

3.1 Research design

Our paper examines data from the implementation of a theory-building lesson, which was part of a larger design-based research project [38] aimed at the development and investigation of middle school theory-building instruction. The lesson took place near the end of a 9-day unit focused on sound energy. The students had already been introduced to sound production, wave propagation, and concepts such as kinetic and potential energy. The lesson (which had originally been designed to take two days but was extended to four) had been co-designed to help the students understand how sound energy moved through a medium as a wave, and more specifically the relationship between a sound wave's volume and energy. To support their knowledge development, the lesson engaged students in building a block-based model of a sound wave propagating through a medium. They then explored the model to infer the relationship between volume and energy. The teacher had co-designed the *Sound* model (Figure 1) with our research team through a process outlined below. This paper investigates the teacher's implementation of a whole-class discussion that took place near the end of the second day of the computational modeling lesson, and her reflections on her implementation of that activity.

3.2 Research context and participants

The implementation took place in the classroom of a teacher we call Ms. K, who taught 8th grade science at a public middle school in the rural Mountain West of the United States. The focal class period had 32 students. All students included in the analysis were given pseudonyms. At the time of the implementation, Ms. K was in her 20th year as a classroom teacher.

3.3 Co-design process

To develop our theory-building lessons, we leveraged a co-design approach and collaborated with area teachers to create lessons that aligned with their needs [39]. Co-design enables teachers to contribute their professional experience to create curricula and lessons that both align with their teaching practices and are useful and sustainable in their classrooms [40]. Through this iterative approach to design, we worked with teachers over two years, asking them to reflect on their practice and work in partnership with us to unpack the relationship between theory building and responsive teaching. Ms. K participated in iterative co-design workshops across two summers with two other local middle school science teachers and the research team. Both summer workshops took place via Zoom. The goal of the first summer was to familiarize teachers with theory building and co-construct a goal for the project. The goal of the second summer was to iterate on the models and develop activities that positioned the models in the teachers' existing curriculum.

In the first summer, we completed a four-week intensive workshop, where we met for several hours five days a week. Over the course of these meetings, the teachers were introduced to the concept of "theory building" as a family of science practices, which included explanation and modeling as outlined in the NGSS, and computational modeling as a form of theory building. Through our co-design process, the teachers developed block-based computational modeling microworlds for phenomena they covered during the school year.

In the second summer, the teachers met with one member of the research team once a week over the summer and as needed in the fall to develop theory-building activities that leveraged the computational models they had designed in the first summer workshop, and which utilized and fit into their existing curriculum and lineup of activities. An underlying goal of the activities was to help students articulate, evaluate, and refine their ideas. Activities were therefore designed with attention to moments when students would be encouraged to share their thinking and consider and interact with each other's thinking. These included activities such as poster gallery walks, which were more student-centered, and activities that required more teacher facilitation, such as whole-class discussions. In their co-design of the computational modeling microworlds, teachers focused on creating blocks that would match student intuitions and on developing models that could be explored to help students understand causal relationships underlying phenomena. An implicit goal for the teachers was therefore to elicit and respond to student ideas.

3.4 Co-designed modeling microworld

The *Sound* modeling microworld was co-designed by Ms. K and the research team using the NetTango [12] interface to Netlogo [9]. NetTango uses a block-based modeling language to make the computational power of NetLogo accessible for science classrooms. NetTango blocks are not a full programming language, but rather, blocks relevant to a domain that is modeled. The *domain blocks* [41] are primitive elements of code that can be combined to model a specific phenomenon.

The *Sound* modeling microworld is shown in Figure 1 [42]. The image on the left shows the *world* that depicts the activity of the agents that are programmed to behave according to the rules specified by the model, which the student builds using available domain blocks. The *setup* and *go* buttons are controlled by *setup* and *go* procedures. These procedures must be programmed in the modeling field using blocks from the block library (right).

Figure 1: The *Sound* modeling microworld, featuring the model built by Ms. K.

3.5 Data collection

Data were collected for the duration of the lesson, which was originally scheduled to run Tuesday and Wednesday, but was extended by Ms. K to include Thursday and Friday. Data were collected during Ms. K's second period class each day. Each class period lasted one hour. Data were collected in the form of video footage, researcher field notes, student work, and teacher interviews. Two video cameras were used to capture the lesson's implementation. One was positioned at the back of the classroom to catch the activity of the group and the teacher at the front board. The second camera was positioned beside a small group, to capture their activity and discussions. An interview was conducted with Ms. K following the end of the unit, to gain insight into her experience implementing the lesson. The interview took place via Zoom and was video/audio recorded. The audio from the video recordings of the implementation and interview were transcribed.

3.6 Data analysis

Our analysis focuses on a whole-class discussion that took place during the end of the second day of the computational modeling lesson. We selected this class discussion as it captured Ms. K's first enactment of responsive teaching for the co-designed lesson. We are choosing to bound our analysis based on our own intrinsic interest in the phenomenon of responsive teaching [43]. We identified one instance where a teacher was engaged in responsive teaching and wanted to deconstruct and understand how it happened and in particular, how the co-designed technology (the *Sound* modeling microworld) played a supporting role. The particular discussion we selected had been intended by Ms. K to be a "wrap-up" discussion at the end of the lesson.

Both video and transcript were analyzed to understand how Ms. K engaged in responsive teaching during the discussion and how the co-designed technology supported her in eliciting and responding to student ideas. A fine-grained [44] grounded [45] qualitative approach was used to create a temporal decomposition [46] of the class discussion and identify the moves through which Ms. K elicited and responded to student ideas. In our analysis, the trajectory of the discussion is parsed into 7 moves, which Ms. K enacted in sequence. Each move is illustrated with segments of transcript and characterized through the lens of responsive teaching, as either a move to elicit student ideas, or a move to respond to student ideas. We analyzed the class discussion to understand Ms. K's implementation of responsive teaching. To understand her experience implementing responsive teaching strategies and the co-designed *Sound* model, we examined the transcript from an interview during which she reflected on her experience teaching the *Sound* unit.

4 FINDINGS

Our findings are divided into two sections. The first section walks through Ms. K's facilitation of a whole-class discussion to illuminate how she engaged in responsive teaching and how the co-designed technology supported her in eliciting and responding to student ideas. The second section examines Ms. K's reflections on her experience facilitating the whole-class discussion to shed light on her experience implementing the co-designed technology and responsive teaching strategies and to identify foci of future co-design iterations.

4.1 Responsive teaching in the context of a whole-class discussion

Below, we examine how Ms. K engaged in responsive teaching in the context of a wrap-up activity, which took place at the end of the last hour-long class period planned for the *Sound* unit. Earlier that period, the students had finished constructing their *Sound* models and responded to questions meant to help them explore relationships between system elements and behavior. We present a narrative account of the last 18 minutes of class, dividing the narrative into activities associated with particular moves made by Ms. K to elicit and respond to student ideas.

4.1.1 Eliciting student ideas: Asking each table to share an idea. With about 18 minutes of the period remaining, Ms. K engaged the students in an activity meant to help them publicly articulate their thinking. She asked them to work with the other students at their table to compile lists of the main points they learned from the simulation activity. She asked each student to contribute one main point, which resulted in lists of about 4 main points per group. She then called on one representative from each of the eight groups to share a unique main point, which she recorded on the whiteboard at the front of the classroom. The activity took about 10 minutes. The list on the board read: 1) If you change the pitch, the particles move faster, 2) Closer the person is, the sound is more bigger, 3) The louder the volume, the greater the sound waves, 4) When it's quieter or louder, the speed changes, 5) The medium can change how fast the speed in a certain direction, 6) The closer the listener gets to the speaker, the further the energy moves, 7) A lower volume has a lower wave, 8) Amplitude affects volume.

4.1.2 Responding to student ideas: Focusing students on making sense of one part of one idea. With about eight minutes remaining, Ms. K turned to engaging the students in a whole-class discussion meant to help them carefully consider and make sense of the ideas they had shared. She stood in front of the whiteboard at the front of the classroom (Figure 2). Written on the board to her left was the list of the eight main points. To the right of the list was a projection of Ms. K's computer screen, featuring a correctly coded *Sound* model, which had yet to be initialized and run. Ms. K waited until the room was quiet and then addressed the students.

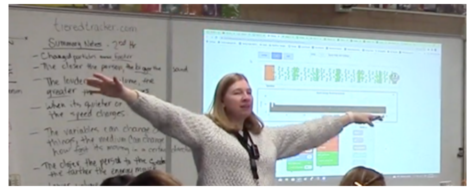

Figure 2: Ms. K stands in front of the whiteboard and addresses the class.

> Ms. K: OK, here's what I wanna do. There are a lot of ideas on the board. I'm gonna pick a couple of these statements to focus on for a few minutes just as we wrap up. We have people saying things like "faster," "greater," "louder," and I'm not sure we're all talking about the same thing. So, I'm gonna put it up here like you tell it to me and let's see if we're talking about the same thing, OK? So, I wanna do like this one right here: "The louder the volume, the greater the sound waves." That's... The greater the sound waves...What does greater the sound waves mean and look like? Could we write that, so that we know what is greater about the sound waves?

Ms. K selected the third statement on the list and read it aloud. She problematized the specific clause "greater the sound waves," asking students to clarify what that meant to them. In doing this she asked them to improve their initial articulation by more precisely describing "what is greater about the sound waves."

4.1.3 Eliciting student ideas: Running the simulation with low and high volume and asking students to identify what is greater about the high-volume sound waves.

> Ms. K: So, I'm gonna go down here, I'm gonna change the volume, first low, you're gonna watch, everybody's gonna watch, you tell me what is becoming greater about the sound waves. So, here's a low volume [uses smartboard to set the speaker to low volume], low volume. Now here's a high volume [uses smartboard to set the speaker to high volume], high volume.

Ms. K turned to the projection of the *Sound* model, using her smartboard pen to open the volume parameter and lower the volume of the speaker. She started the simulation, waiting for about a minute while a train of longitudinal wave fronts propagated through the air particles between the speaker and listener. She then paused the simulation and raised the volume of the speaker. She waited while a new train of wave fronts propagated from speaker to listener. In using the technology in this way, Ms. K gave the students concrete images to compare to consider what quality of the sound wave might be greater for the high-volume wave. The simulation allowed her to present them with real-time experimental results, or data from which they could infer what was greater about the sound waves when the volume was increased. This is important, as the students who did not suggest the main point may not have previously noticed the "greater sound waves" phenomenon and the students who did write the statement may not remember what they had meant by it or they may not have thought about it enough to articulate what precisely was "greater about the sound waves." In doing this, Ms. K sets all of the students on equal footing with regards to addressing the question "what is greater about the sound waves?"

Ms. K walked back over to the list of student ideas and read the focal statement aloud again. She looked out at the students and asked for a volunteer to tell her what "greater sound waves" might mean. In doing this, she asked the students to connect what they saw in the simulation with the relationship one group of students had described. She asked them to use evidence from the simulation to elaborate and make more precise the original main point. Ms. K pointed to a student and asked her to share their thoughts on "what is greater about this wave."

> Ms. K: What is greater about it to you?
>
> Penny: The more, the more the waves are moving through.

4.1.4 Responding to student ideas: Using the simulation output to test the student's idea.

> Ms. K: You think that there are more waves moving through? Did you count them?
>
> Penny: No.
>
> Ms. K: Can I count them? Is that OK? OK, so from 200 to. . . well, we'll do from 300 to 400, I'm gonna count them. Let's see. We've got one wave, two wave, three wave, four wave. . .

The student responded to Ms. K's question with a specific, testable hypothesis. Ms. K asked whether the student had counted the waves. The student had not, and Ms. K asked if she could count the number of waves. She counted four waves over a period of 100 ticks (from t = 300 - 400). It is likely that Ms. K knows that changing the volume should not change the number of waves, and she is using the simulation to gather data with which to refute the student's hypothesis and determine that it is not the number of waves that is greater about the sound wave, when the volume is increased.

> Ms. K: Now let's change it and I'm gonna count 'em again and see if that is true. So, I'm gonna take the volume back down. And let's let it run for a minute. Let's see if there are more waves or less waves in 100 ticks. K, we're starting to get some data here. . .So, I'm gonna stop it for just a second. . .So, here are our 100 ticks, one wave, two wave, three wave, four wave. Are we getting more waves when we change the volume? Or less waves?

Ms. K lowered the volume and counted the number of waves over the same interval (100 ticks). She counted the same number of waves she had counted for the high-volume sound wave. She asked the students to compare the number of waves for the low volume wave with the number of waves for the high-volume wave, hoping to refute Penny's hypothesis. No students responded to her request, so she turned to Penny.

> Ms. K: Can I ask you? 'Cause we were the ones that were talking about it. Does the data show that?
>
> Penny: Yeah.
>
> Ms. K: So, look we've got from 300 to 400, it's the same [points to 100-tick interval]. So, when you tell me "the louder the volume the greater the sound waves" are we talking about a greater number of waves? When we say "greater the sound waves" what is greater? I'm not sure we've got to the bottom of this yet. Somebody suggested that maybe greater means we have more waves when we take the volume up. But we just counted them, and there's four waves in between the same number of ticks. We're not getting more waves that way.

Ms. K asked Penny, who had originally offered the "more waves" hypothesis, "does the data show that?" She responded with a short "yeah," which Ms. K did not pursue further. It may be that she senses hesitation in Penny's voice and is worried about putting her on the spot. It may be that she is worried she won't give the correct response, and she wants to make sure the students understand that the hypothesis was refuted by the data produced by the simulation. At this point, there were about 3.5 minutes remaining in class and it is possible that Ms. K felt pushed to make connections for the students, rather than letting them take the time they need to arrive at the connections on their own.

4.1.5 Eliciting student ideas: Running the simulation with low and high volume and asking students to identify what is greater about the high-volume sound waves.

Ms. K turned back to the students to solicit additional possible meanings for "greater waves."

> Ms. K: I'm gonna play this one more time. Turned up the volume. What is greater? What is greater about this?
>
> Henry: The waves look bigger.

4.1.6 Responding to student ideas: Helping students see important relationships in the simulation.

> Ms. K: The waves look bigger. . .What is causing that? What piece of this model is causing the wave to be bigger?
>
> Henry: The particles.
>
> Ms. K: The particles are causing themselves to be bigger? What's causing the particle wave to wave bigger?

Henry suggested that "the waves look bigger." While somewhat vague, Ms. K may have recognized that the idea was heading in the right direction. She asked Henry what was causing the waves to be bigger. This move may have been to help the students make logical connections between cause and effect in the model, which would ultimately allow her to connect the idea with the concept of energy, her lesson's learning objective. Henry wasn't able to answer her question, so Ms. K tossed the question back to the group.

> Ms. K: Does anyone know what I'm asking here? What piece of the model is causing the wave to be "bigger?"
>
> Javier: The speaker.
>
> Ms. K: The speaker! [nods and points to the speaker in the microworld]. Isn't it true that the volume affects the speaker? So, you set the volume, right?

> That tells the speaker what to do and the speaker controls what the particles do. Is that the correct statement? So, can I go back and - who just told me this - that it was moving. . .
>
> Henry: It looked bigger
>
> Ms. K: It is a bigger wave! So, bigger in what way? Look, watch my hand here, whoops! Too far [traces front end of speaker back and forth with a whiteboard marker to capture its displacement as it vibrates]. See what the speaker is doing? If I turn the volume down, watch what the speaker does.
>
> Javier: The movement of the speaker. . .
>
> Ms. K: The movement of the speaker is - watch! I'll turn it down [adjusts speaker parameter to lower volume]. How could you describe the energy of this speaker? Does it have a lot of energy? Does it have a little bit of energy? How do you know? We've studied energy since the beginning. . .How do you know that this speaker has a lot or a little? Right? It's moving a lot or moving a little. . . So, let's think about this. . .when it's moving a little it only has a little bit of movement, a little bit of energy, where is it giving that energy? It's giving it to the wave, right, to the particles, and the particles - little bit of movement here, right - a little bit of squish, vs. let's look at this - a lot a bit of squish, right? - pushing those particles way far.

Building on Javier's idea, Ms. K drew students' attention to the speaker and how it moved back and forth with a greater displacement for the high-volume sound, as compared to the low volume sound. She then connected the speaker's movement with its energy, asserting that when the speaker moves a little, it has a little energy. She asked the students what the speaker gave its energy to, but didn't wait for them to respond, asserting that it gave its energy to the particles whose movement comprised the wave. She then compared the amount of speaker movement with the amount of wave "squish," asserting that a little bit of speaker movement resulted in a little bit of squish, while a lot of speaker movement resulted in a "lot a bit of squish." It is reasonable that Ms. K is making these connections for the students, as she is attempting to tie everything together and leave the students with a clear takeaway in the 30 seconds remaining before the bell rings.

4.1.7 Responding to student ideas: Connecting simulation data with scientific terms and student ideas. Ms. K returned to the statement she had opened the discussion with.

> Ms. K: So, I'm going to come back to what I said in the beginning. When we say, "the louder the volume the greater the sound waves" [bell rings]. Uh oh. We will revisit this at the beginning of class tomorrow.

Ms. K read the statement aloud, presumably planning to review its more precise articulation and connect that with speaker energy/movement and wave energy/squish, but was cut off by the bell, which signaled the end of the period. She resolved to pick up the students' thinking at the start of the period the next morning.

4.1.8 High-level sketch of responsive teaching strategies enacted during the whole-class discussion. The analysis presented above walks through a whole-class discussion during which Ms. K elicited students' ideas and then focused their attention on making sense of an idea offered by one group. Her goal had been to use the discussion to move from the students' own words to the scientific relationship between a speaker's volume and the energy of the wave it produces. In leading the class discussion, she enacted a number of moves to elicit and respond to student ideas, including moves directly dependent on the technology she had co-designed. To elicit students' initial ideas, she asked each table group to share what relationships they had observed in the *Sound* model. Responding to those ideas, she selected one idea ("the louder the volume, the greater the sound waves") and then focused students on making sense of one part of it ("the greater the waves"). She elicited more ideas by running the simulation with low and high volumes, asking students to identify what was greater about the sound waves produced by the louder speaker. Responding to the ideas shared by students in response to this activity, she enacted a number of strategies, including using the simulation's output to test a student's idea, and helping students see important relationships in the simulation. She connected students' ideas to science terms in order to build on their thinking and approach her learning objective in just 8 minutes.

4.2 Ms. K's reflections on the discussion

Directly following her implementation of the activity, Ms. K walked up to the researcher operating the video camera and said: "You just don't know what they don't know until you start poking around. . . and then it's absolutely terrifying!" She resolved to change her plan for the rest of the week, spending two additional class periods unpacking students' thinking about sound waves in the context of the simulation and concrete phenomena. During a follow-up interview, Ms. K shared that something she felt had gone well about the lesson implementation was the computational model she had co-designed.

> I had a lot of reservations about using, you know, the coding in the class, I've never done it before. So, going into it, I have a lot of reservations about my ability to teach that to the students and have them use it effectively. And I was overwhelmingly pleased, all the way across the board. There were a few people who didn't have the model working, but that just lent itself towards good conversation. And it wasn't a problem. And so, I had expectations that things were gonna be really bumpy. And they worked. And so that was a huge plus.

Though she felt nervous about how the students would respond to the part of the lesson where they would be asked to code the *Sound* model, she ultimately took the risk and implemented the activity. Her confidence may have been buoyed by the fact that she had an intimate understanding of how the model should look and run when built correctly, as she had helped to design it. Ms. K shared that one thing that had been challenging about the lesson implementation was not being able to spend the time to really dig into student ideas. Her feelings connect with the tensions noted in the responsive teaching literature described in the introduction, in particular, the tension between supporting students' achievement of content objectives and allowing them to follow their own thinking to develop knowledge in a more organic way.

> When we're looking at this. . . they've generated all these ideas, and it's just, I don't know, it's kind of disheartening to kind of like, just wrap it up really quick. And, you know, you gotta give a quiz and, and it's not that we're never coming back to anything, we're still talking about waves. . . but I don't know, it just, it breaks my heart, that we don't have time to just really dig our teeth into these ideas. And, and, you know, flesh them out more and, and really try to help the kids make sense – more – of the phenomenon.

When asked whether she would implement the unit again and if so, if there was anything that she would change about it, Ms. K responded that she would like to implement the unit again, that she was feeling more confident especially with having the students build the computational models, which had initially been the greatest source of worry for her. As for what she would change, she talked at length about needing structures to help students share and make sense of their ideas.

> The day before we did that list on the board, I did not know how to elicit this. We don't have a lot of structures being taught to us as, especially as science educators, for how to get the kids to get their thoughts out there, how to organize them, and then how to, like organize them as a class, sometimes they call this consensus – coming to consensus and that kind of thing, consensus building. And we are never trained on this. And then so here I am – got this huge list on the board. I didn't have time to go any further. But like, so what do I do with that? What do I, you know what I mean, I have no structures in place. And so, we just came to this like Grand Place. And then we tidily wrapped up the unit and we, you know, moved on. And I don't know, we need structures.

5 DISCUSSION

From the analysis of classroom data, it's clear that technology played a central role in Ms. K's enactment of responsive teaching strategies. The simulation was at the heart of the activity, as its objective was to help students make sense of their observations and infer the relationship between the volume of a speaker and the energy of the sound wave it produced. The simulation also played a central role in many of the strategies Ms. K enacted to elicit and respond to student thinking. She used the simulation to elicit student ideas during the whole-class discussion by running it at low and high volumes and asking students what was "greater" about the high-volume wave. She used it to respond to student ideas, testing one student's idea to see if higher volume corresponded with more waves, and to help students see relationships between speaker volume and wave energy illustrated by the simulation. From the analysis of Ms. K's reflections on her teaching, it appears participating in the design of the technology supported her integration of the simulation into her teaching. Though she had reservations about implementing the part of the activity where students used the blocks to code the *Sound* model, she understood how the model should run once correctly built, because she had designed it to look and work a particular way. Perhaps it was this that gave her the confidence to implement the activity. In reflecting on her experience, she identified what was still missing for her to feel truly confident in enacting responsive teaching. This was a collection of strategies with which she could elicit and respond to student ideas. Her request provided the seed for our next iteration of work together, where we will co-design explicit strategies for eliciting and responding to student ideas in the context of theory-building activities, including the construction and exploration of computational models.

Taken together, findings from the analysis of classroom data and Ms. K's reflections suggest that responsive teaching can be supported by the use of computational modeling microworlds and that teachers' implementation of such technology can be supported by involvement in its development, through a co-design process. The study suggests implications for the design of computational modeling microworlds that support responsive teaching. For example, a simulation should be able to test student hypotheses and provide enough visual detail to refute or support their ideas, as appropriate, as demonstrated by the case of Ms. K testing and refuting Penny's idea about a louder volume sound corresponding with more waves. A simulation should also provide enough visual detail that students can observe the relationships between system parameters and behavior through multiple representations, as demonstrated by the case of Ms. K guiding student attention to the relationship between the speaker's movement and the resulting "squish," and therefore energy, of the wave. The study also suggests that teachers' implementation of the computational modeling microworlds would be best supported with explicit strategies for eliciting and responding to student ideas. The teacher expressed low confidence in her ability to enact these aspects of responsive teaching, and her feelings are likely not unique. By developing strategies that leverage technology to elicit and respond to student ideas, we can help teachers gain confidence with implementing both responsive teaching strategies and computational technologies in their classrooms.

6 CONCLUSION

In this paper, we examined Ms. K's enactment of responsive teaching strategies during a whole-class discussion, along with her reflections on the experience. The whole-class discussion was her first experience with eliciting and responding to students' ideas. Our analysis highlighted the ways she helped her students articulate and evaluate their ideas, characterizing her moves in detail over the discussion, during which she tried to help the students make sense of the student-generated idea "the louder the volume, the greater the sound waves." The paper examined how her implementation of responsive teaching was supported by her use of a computational modeling microworld she had co-designed with our research team. It discussed her experience of the implementation, identifying how the co-design process may have supported her confidence in implementing the technology, and naming foci of future co-design iterations. The paper makes empirical contributions to literature concerned with responsive teaching, literature concerned with engaging students in computational modeling in the science classroom, and literature concerned with processes of teacher/researcher co-design.

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