Grounding Computational Abstractions in Scientific Experience

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Abstract: Opportunities for computational modeling bring about new and productive uncertainties in students' explanations of the relationship of phenomena "in the world" to their models of those phenomena. Computational abstractions that become useful in the lifeworld of the classroom are steeped in the history of how those abstractions came to be used and understood. In this paper, we describe how two elementary classrooms used a programming and modeling language in ways that link their material enactments, measurements, and paper-based forms of representations to productive computational abstractions. The heterogeneity of computational abstractions—and how they came to enter the shared language within these classrooms—have implications for our understanding of how learners perceive their shared production of scientific explanations and the computational and non-computational tools they use. Findings have implications for the design of programming environments and for K12 computational modeling, both in regard to science education and computing education.

Keywords: model-based reasoning, science education, computing education

Introduction

Science education scholars within a science-as-practice perspective view learning science as involvement in a "mangle" (Pickering, 1995) among theories, instruments, and representations (Lehrer & Schauble, 2006; Manz, 2015). In this view of science, the experience of scientific work is non-linear and is steeped in productive representational uncertainty (e.g., Manz, 2018). Given the current momentum to leverage programming and modeling in K-12 science education (Wilensky et al., 2014), an obvious question then arises in the form of how students and teachers interpret and use computation in the context of scientific modeling in their classrooms. While a few scholars have tried to answer this question, in most studies, the classroom work is predominantly led by researchers (Sherin et al., 1993; Wilkerson & Wilensky, 2015; Pierson et al., 2019). The goal of this paper is to present a more *phenomenological* (Sengupta et al., 2018, in press) view of how students and teachers take up computational modeling in two science classrooms. In each classroom, we focus on how teachers and students used both computational and non-computational representational forms of representation and modeling to investigate motion as a process of continuous change. A key theme across the two classrooms is the heterogeneity in students' modeling, as evident in how they distributed the intended scientific meaning across various forms of modeling.

Theoretical and conceptual background

There is now a growing body of evidence that suggests that computational representations within programing and modeling environments, as well as other complementary forms of representations outside the computer, need to be considered relevant and necessary for the integration of agent-based programming and computational modeling in elementary and middle school science classrooms. For example, Dickes et al. (2016) and Danish (2014) showed that embodied modeling and the creation of physical representations of change over time can serve as powerful anchors for grounding multiagent-based programming and modeling in the context of learning about complex ecological systems. Similarly, our previous work suggests that physical modeling of motion (e.g., using cars and ramps) can offer 4th and 5th-grade students important opportunities for reflection and refinement of their own agent-based computational models by alerting them to the need for properly initializing their models (Sengupta & Farris, 2012). And finally, drawing upon findings from a series of design-based professional learning sessions with 56 teachers in K12 public and charter schools, Sengupta et al. (2018) showed that (a) when teachers, with little or no background in programming, view programming as a way to "mathematize" the world, they can integrate programming and modeling with their science curricula; and (b) the use of multiple and complementary forms of programming and modeling (e.g., physical, virtual and embodied) can facilitate such integration.

These studies suggest that a view of practice as a *dance of agency* (Pickering, 1995) is essential for integrating computing and science education in the K-12 science classroom. Specifically, these studies suggest that programming and modeling activities should be in conversation with the forms of investigations and representations that students already use to investigate phenomena, in our case, motion. These include representations such as dot traces, velocity and displacement graphs, and word problems, as well as investigation of "real" objects in motion. Pickering (1995) describes scientists' work as a "mangle" among theory and instrumentation, a dance between scientists and the models they use to represent the world. In order for computational representations to find their place in a productive "mangle" that is appropriate for young learners and for classrooms, computational representations must enter into dialogue with investigations and non-computational representations that students were using to explain the world (Sengupta et al., in press). Without continuity—from the learners' perspectives— of the computational modeling work with their other forms of modeling and emerging theories, there could be no "dance" of agency. Our goal is to investigate how teachers and students experience this dance of agency in the context of modeling motion using agent-based programming in their "everyday" science classroom, by using multiple (heterogeneous) representational forms and practices in dialogic relationship with one another, guided by the teachers' re-framing of programming as a way to help their students model and measure motion as a process of change over time.

This goal only partially aligns with current views of abstractions in the computing education literature. According to Wing (2008), the "nuts and bolts" (p. 3718) in computational thinking involve dealing with computational abstractions in the following ways: a) defining abstractions (e.g., algorithms, programming languages, etc.), b) working with multiple layers of abstraction, and c) understanding the relationships among the different layers (Wing, 2008). As Sengupta et al. (2013) pointed out, these aspects of working with computational abstractions are synergistic with scientific modeling. However, Wing (2006) emphasizes the generalizability of computational abstractions as the source of computational power, which in turn give computer scientists the power to scale and deal with complexity. A phenomenological interpretation of Wing's notion of abstractions is incomplete without a deeper understanding of the contextualization that necessitates and grounds computational abstractions in professional practice (Sengupta et al., 2018). For example, Schmidt (2006) points out that software researchers and developers typically engage in creating abstractions that help them program in terms of their contextualized design goals —e.g., the specific problem that they are solving, which is often in a different field (domain) of professional practice (Sengupta et al., 2013). Therefore, abstractions in computing are usually grounded in disciplinarily relevant (or contextually relevant) epistemic and representational practices.

An important question, then, is what does a contextualized and phenomenological view of computational abstraction afford for children's design of abstractions? This is the question we seek to answer. We illustrate how computational abstractions are created and re-created in both virtual and physical forms in two teacher-led classrooms in elementary grades in the context of modeling kinematics. The first is less successful than the later one, and we explore why. We also illustrate how the work of modeling was distributed across computational and physical representations. Attending to these forms of heterogeneity, we contend, is important for understanding how teachers and students with very limited prior experience in programming can take up computational modeling as a language for doing science. In the final section of the paper, we discuss the implications of our study in terms of the design of computational modeling platforms and activities for classroom integration in K-12 science.

Methods

We conducted a design-based research study (Cobb et al., 2003) in two different classrooms (Grade 4, in an elementary setting; and Grade 5, in an early middle school setting), with the central aim of understanding how agent-based computational modeling can be integrated in science classrooms. Both classrooms were part of one publicly-funded charter organization in a large metropolitan area in the mid-South. Classroom A was a Grade 5, gender-segregated (all female, as identified by the school) science class with 16 students. The data from Classroom B were collected in a mixed-gender 4th-grade classroom, during math and science time. In each of these classrooms, the same team of researchers worked in partnership with the respective classroom teachers to integrate agent-based programming and modeling within the existing science curricula over a period of approximately 9 months using a program developed by the authors for visual and multi-agent programming (ViMAP; Sengupta et al, 2015). Plans for instruction were driven by the teachers, and continued development of the ViMAP environment followed the needs and emergent goals in the classrooms. The overall design of curricular activities was guided by our conjecture that teachers and students would adapt the computational media environment to meet learning goals, and we wanted to understand how this took place and to what ends.

In Classroom A, lessons were often co-taught by the teacher and one researcher. In Classroom B, instruction was almost exclusively directed by the teacher, although the teacher and researchers usually planned together. The data include video of each class, interviews with students and student groups, student work, planning documents and discussions of the teacher and the researchers, photos of whiteboards and other representations, detailed field notes from each session, and automated screen captures from the students' computers.

Findings and analysis

Case 1: Graphing as folding and unfolding processes of change

In the 5th grade classroom, we asked students to describe what happens to the speed of a ball after it is dropped from near the ceiling of the classroom. Students did this work in small groups, and two dominant stances emerged in the classroom talk: the ball was (1) speeding up or (2) keeping about the same speed as it fell. We also watched a video of a ball falling with a stroboscope flashing on it, therefore illuminating the positions of the ball at each consecutive interval of time. The video was pulled from YouTube, not made in the classroom, and students needed support to unpack the many unfamiliar features of the video. Since we wanted students to eventually attend to the distances in-between successive positions of the ball, the first author used the video to compile all the visible positions of the ball into one image and printed them on strips of paper (Figure 1, left). The following day, students attempted to create folded representations of the speed of the ball, similar to those shown in Figure 1. We intended this process of *folding* acceleration—that is, taking the total distance traveled and breaking it into segments traveled in same-size increments of time—to support students' understanding of discretized (bar graph) representations of speed. When the paper is positioned to stand on its edge, as in the first photograph, it shows a pattern of change in the segments that was similar to shapes students had made in an earlier unit that focused on geometry and shape drawing. We illustrate these representational gymnastics with the following episode from Shenice and Imani:

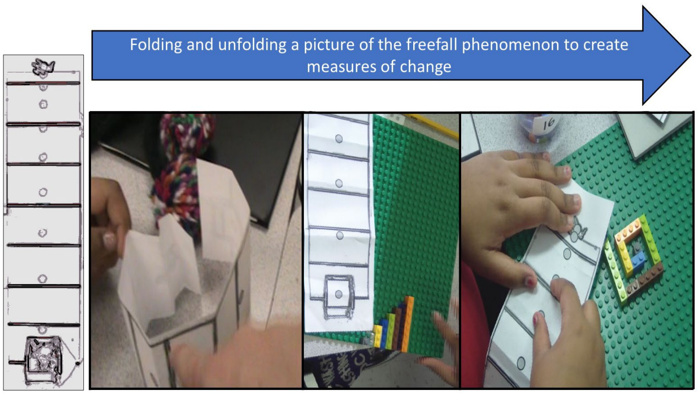

Figure 1. Folding and unfolding a modified picture of the freefall phenomenon. From left to right: Students were given strips of paper with images of the positions of the ball, Shenice's folded representation of the distance traveled in each step, students' graph-like Lego representations of changing speed.

In this excerpt of interaction, Shenice and Imani were working on their folded representations when the first author asked them to explain their models. Imani first described folding in "every space", creating approximately equally spaced sections. Shenice offered an alternative suggestion: "You could fold it in-between the balls." Amy then asked Shenice to explain her model:

Amy: Shenice, can you tell me what this means? (laughing) So, like, if I..how am I supposed to look at it?

Shenice: Well, I don't know. I just folded, tried to fold in-between each ball.

Amy: Okay-

Shenice*:* *(motions to all of the positions of the ball)* All of the balls going down, like this space is just free, because it has nothing. Because the ball could have fell anywhere in this space.

[Some sensemaking about folding between the balls removed for space]

Amy: Okay, so the spaces between your folds, if we look at it like this (arranges paper so that she and Shenice see it from a birds-eye view) I see short, a little bit longer, a little bit longer, a little bit longer. So how is that showing something?

Shenice: It start off short, but it gets longer. It comes closer together and then separates. Cause, the faster it goes, the more it spreads.

Amy: So are you saying that it starts close together, then it gets further, then it gets closer again? Is that what you are saying?

Shenice: No. It starts closer, but as it, it starts to go faster, as it goes faster it starts to separate.

In the next class meeting, we agreed with the teacher to refocus the students on the positions of the ball. As students flattened their folded representations from our previous meeting, they measured the "space between" the positions of each image of the ball and the one immediately beneath it, as shown in Figure 1 (right). During this activity, students came to use a shared word for the spaces between the positions: "gaps". Within this sequence, students then translated the gaps to discrete distances, that can be compared and arranged in bar graphs, as is shown by Imani's right thumb and index finger in Figure 1. This form of symbolization was intentionally linked to the ViMAP representations students had been making (see Figure 2 for an example). In our computational modeling environment, paper folding, and the Lego activities, the speed for each gap was represented with discrete bars (instead of a continuous line graph). Students used the height of the Lego bars (that is, the height of distance traveled in each moment) to describe that the distance between the positions was *steadily increasing*, our definition of constant acceleration in this classroom.

Analysis

There are several representational challenges in this interaction. The video that we selected included the background of bold black lines, which were retained in the printed images. Imani and Shenice work to sort out what aspects of this representation were most pertinent to the question about the speed of the ball: Imani wants to fold "in every space," and ignore the positions of the ball. Shenice attends to the space between the bold black lines and the images of the positions of the ball. She describes that she is "tr[ying] to fold in-between the balls." She has also noticed that one space between the black horizontal lines does not have a position, and is uncertain how to fold the spaces: "this space is just free, because it has nothing."

In spite of these representational challenges, Shenice placed her folds immediately above or beneath each of the images of the balls, and she describes the pattern of change in the distances between the folds near the end of this exchange: "It starts closer, but as it, it starts to go faster, as it goes faster it starts to separate." Her use of the word "separate" indicates a possible slippage between the static image and the dynamic process of change that it is intended to represent. Classroom A students introduced the word "gap" to describe the spaces between positions, it continued to be useful to the research team in future iterations of this work, as we describe in Case 2.

Case 2: "Gaps" and "flags" as computational events

Students in Classroom B investigated motion by first measuring constant speed using Lego robots, followed by investigations of acceleration using balls on inclined planes and toy cars rolling across different surfaces. For each investigation, students modeled their data in ViMAP. The teacher, Ms. Beck, insisted that we plan tangible, "concrete" episodes of motion for students to model. The focus of this section is on how these linked forms of representation supported students' use of abstractions that were grounded in their experiences of the phenomenon (Farris et al., 2019). In the constant speed work, we introduced paper flags as a marker of position. Initially, these were 4-inch paper adhesive strips which students placed along the path of the robots as a physical form of the dot-trace representation (Figure 2, left), a long-supported LOGO-based representation of motion in introductory physics (Hammer et al., 1991; Sherin, 2000; Schwarz & White, 2005; Sengupta & Farris, 2012).

In ViMAP, the marks of position were symbolized as "measure points" with the symbol and the command "place measure point". Rather than repeat challenges similar to those with the stroboscopic video in Classroom A, we designed instruction so that students created their own videos of motion. Students did not differentiate in their language between these physical and computational symbols, and almost always referred to them as "flags" or "measure flags", in spite of the language in the command "place measure point". Figure 2 shows one group's work in the material and tangible measurements in the school gym. They used the datasheet to record distances between flags, which they had attempted to place at 3-second intervals as a robot moved across the floor. The command blocks used in one group member's computational model, which asks the turtle to "go forward" by each measured step size, and "place measure point" as the commands run, are also shown in Figure 2. In this case, the design of the physical activity and the features of the computational environment are closely linked, supporting students to move between the physical, lived space and their own ViMAP programs.

As this work progressed, flags as indicators of a position in time became fluently used and understood among class members, and Ms. Beck and the first author continued to make "flags" available in all physical investigations of motion. On December 2, student small groups were designing investigations for the inclined planes. The central problem was, "How can you convince [the principal] that the marble is changing speed? Students' strategies were varied, but all included making and comparing measurements of time from the beginning position to one or more "flag[s]", and to the end of the ramp. Our work with ramps and videos called for finer (i.e., smaller scale) measurements, so we used smaller (approximately 1 inch) adhesive flags with arrow-shaped ends. The excerpt shown in Table 1 is taken from Ms. Beck's questioning of a small group as they set up an investigation to demonstrate evidence that the speed of the marble was increasing (Figure 3). They position a tape measure along the ramp. They have a small adhesive measure flag labeled "END," which they place at the midpoint. Bolded text indicates deictic gestures (pointing) that co-occur with talk.

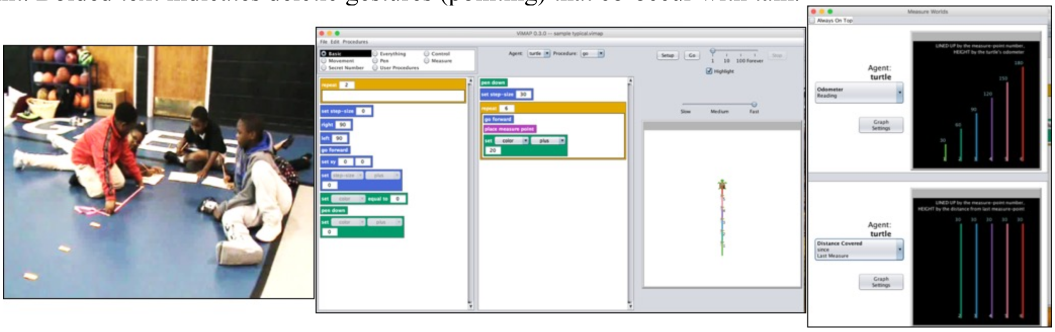

Figure 2. The material enactment, datasheet, and computational models, and graphs in the constant speed work.

Table 1: Demonstrating Evidence that Speed is Increasing

Ms. Beck: Uh, real quick set-up question. Why are you guys measuring right now just out of curiosity? **Aden:** to do the halfway point **Ms. Beck:** Ooooo. I like that. How did you determine what the halfway point was? **Nylah:** Because..we know that two divided into 48 is 24. So when we measure it we know that the..halfway point. **Ms. Beck:** Okay. So first, you all tell me how you all are setting up your experiment..um… Aden, tell me a little bit and then I'll go to each one of you guys. What are you doing today for us today?	
Aden: First, when we.. the ball gets right **here..**	*Aden points to the midpoint "END" flag*
Theo will start the timer, and then when it gets to the edge	*Aden points to end of 48" ramp*
he will stop the timer. Then the next one, we are going to do one when	*Aden points to the beginning of the ramp*
it gets to the **end**	*Aden points to the midpoint flag*
when it starts from **here**	*Aden points to the beginning of the ramp*
he starts the timer and when it gets right **here** he stops it.	*Aden points to midpoint flag*
[Members of group nod.] **Ms. Beck:** Mmkay. Anything you want to add, Nylah? I mean what are you guys trying to prove? Are you trying to prove the same thing? **Nylah:** We're trying to prove that the ball will accelerate or increase its speed.	

Figure 3. (Left) Experimental setup with a small red flag is at the midpoint labeled "END." (Right) Ms. Beck helps to organize features of the students' investigation on the whiteboard with a diagram.

As the students collected their measurements, Ms. Beck organized these in a diagram on the whiteboard (Figure 3). The students release the marble from the top of the ramp and start the timer as the marble reaches the midpoint, and report the time for this segment as 1.4 seconds. They next release the marble from the top of the ramp and stop the timer at the midpoint, and the report the time of 2.4 seconds. Ms. Beck's diagram uses points to indicate the places that the group members have marked as significant, and she marks up this diagram as they conduct their experiment. She represents the beginning, end, and the "end" flag at the midpoint as points, and labels them A (not yet labeled in Figure 3), B, and C.

In students' ongoing kinematic work, measure flags also became labeled with frames of video—therefore associating a position with an instant in time. In the friction unit (Figure 4), students made comparisons of total time traveled based on these marked flags. This comparison created new representational disagreement: students were comparing the time in which a toy car slows down on two surfaces: on a rug (Figure 4, left) and on the tile floor (Figure 4, middle). Due to differences in the camera angle of their setups, students perceived the total distance traveled by the car on the rug to be *further* than the car on the tile—that is, from the still images, the total distance from (a) the flag that is furthest to the left and (b) furthest to the right was a greater distance on the rug in comparison to the tile. This did not match their experience when running their experiments and collecting the video, nor what they expected to happen, that the surface with more friction would cause the car to slow more quickly.

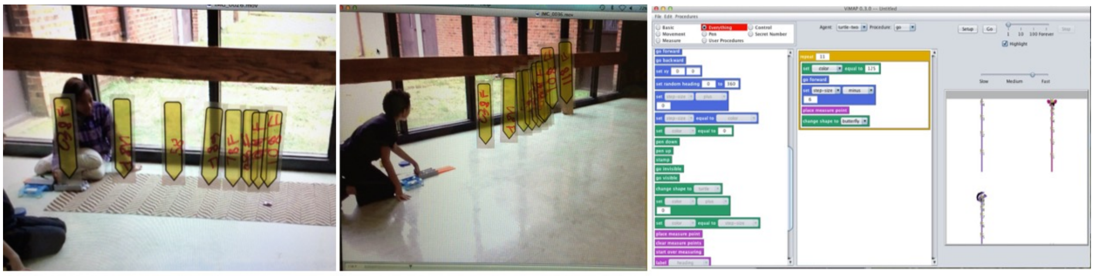

Figure 4. Left: Car path from the launcher on a rug with measurements every 10 frames. Middle: Car path from the launcher on tile hallway, measurements every 10 frames. Right: ViMAP model in which a student describes the car on the tile floor (squirrel) and the car on the rug (butterfly).

The evidence that eventually resolved this conflict came in the form of subtracting the time required for the motion to stop, assuming that the force initially applied is approximately equal in each setup. One of the researchers encouraged students to use the frame numbers as a form of evidence. Students used the frame numbers they had written on the flags like timestamps and calculated the total time of motion on each surface: 118 frames – 38 frames = 80 frames on the hard tile floor, versus 108 frames – 38 frames = 70 frames on the rug. While the difference of ten frames is minimal, the students were satisfied that they had produced evidence that it takes more time to slow down to a stop on the tile (which they argued caused less friction). Figure 4 also shows a student's computer model of the comparison, in which computational measure flags are used to symbolize physical flags marking position in video-recorded motion, and the variable for decreasing step size (set step-size minus x) computationally represents the coefficient of friction on that surface.

Summary: Symbolizing positions, time, and "gaps" computationally

In Classroom A, students first invented the term "gaps" to refer to the distance between successive positions of an object. In ViMAP, this concept was represented with "step-size," —the distance the programmable agent moved forward with each execution of the "go forward" command. Students became fluent in the intended meaning of step-size through material investigations of free fall, folding activities, and the creation of Lego graphs to discretize the total distance into gaps, which supported students' computational work.

In Classroom B, the researcher and the classroom teacher agreed that material enactments were essential for students' learning about motion, initially expressed by the teacher as the need to "make things concrete." In this classroom, we iteratively designed episodes of motion for students to enact or to design investigations of, including the constant motion of robots, acceleration down an inclined plane, and comparisons of forces of friction on different surfaces. In each activity, students used physical "measurement flags." The meanings of these flags became enmeshed and indistinguishable from the command for placing "measure points" in ViMAP, and we believe that this was a key support for students' level of expression in their own descriptions of the motion events "in-the-world", in drawings and diagrams, and computationally as commands to be carried out by programmable agents.

Discussion and implications

Technocentrism continues to be a persistent concern in the domain of children's educational computing, where researchers have focused less on the complexity of the experience of computing in different contexts, and instead have focused more on the assessment of computational thinking (Sengupta et al., 2018). In this paper, we have put forward a view of children's computing in science classrooms in which the focus is on how computing involves not only programming and using computational abstractions within the programming language, but also grappling with the physical and material world in order to create and re-create scientific representations. Central to this image of computing is the notion of the dance between representational forms, as evident in how students came to find meaning in physical phenomena and representations and mirror those in the computational environment, or reuse primitives in the computational environment to describe physical phenomena. Our analysis illustrates some trajectories of students' and teachers' modeling in such classrooms, and furthermore, highlights how their investigations of motion as a process of change over time offered productive pathways for interpreting and deploying computational abstractions.

So, one might ask the following question: What value does computing add to science "as usual"? Latour's (1999) studies of scientists engaged in "doing" science offer an insight: he showed that the creation of scientific knowledge involves a long cascade of representational transformations where scientists iteratively create, share, and modify representations of the relevant phenomena. At each stage of this representational cascade, he argued, the scientific ideas (or objects) become "durable". That is, in science, a thing (or an idea) "can remain more durable and can be transported farther and more quickly if it continues to undergo transformation at each stage of this long cascade" (Latour, 1999; p. 58). Similarly, in our work, children's creation of durable and transportable descriptions of the speed of moving objects requires them to think about and inscribe motion in terms of relationships of displacement and time. Specific ways of describing (and inscribing) properties of kinematic phenomena emerged as key ideas that were durable and frequently reused as children moved across representational means—"gaps" and "measure flags." These conceptualizations moved back and forth across the children's computational, physical, and paper-based representations. Similarly, in Enyedy and colleagues' motion learning environments (2012), motion-sensing technologies were used to transform learners' movements around a room to a microworld. In this present study, children measured motion and re-described it in a way that the computer can understand though programming.

We see these kinds of transformations in scientific reference as deeply related to Pickering's (1995) "mangle". The representations do not merely point to something beyond themselves, they make that reference available for further manipulation and prodding, and the representations themselves then become subject to further re-description and specification. At each stage, references to the target are changed but retain an intact and fundamental meaning across the heterogeneous forms of models. These forms were also durable to heterogeneity in the target phenomena (in our case, descriptions of different kinds of motion phenomena) indicating their centrality to ideas that are of disciplinary importance, rather than superficial features.

Our work has implications for designing computational modeling platforms for K-12 science classrooms in terms of the expressivity and heterogeneity of the representational infrastructure in such platforms. Our work offers insights both in terms of how we can design better software systems, as well as for the design of learning activities, as we explain next. Along the first dimension, our findings suggest that in order to support computational modeling in the context of kinematics, agent-based programming should be complemented by Cartesian graphing functionalities. Commanding the agent's behavior on screen offers an opportunity to "dive in", whereas graphing offers an opportunity to "step out" (Ackermann, 2012). Furthermore, our analysis of the 5th-grade students' work also suggests that students can use these functionalities in different ways in terms of representing relevant variables more explicitly either using graphs or simulations or both. We found that heterogeneous use of this representational infrastructure afforded important opportunities for students to participate in the modeling processes of selection, design, and critique.

Along the dimension of designing learning activities, throughout the analysis, we have described pedagogical decisions alongside descriptions of learning. We found that agent-based programming became reframed by teachers as mathematically modeling the relevant scientific phenomenon. This corroborates other studies where we have also found that elementary and middle school teachers prefer to reframe computational programming, in particular, agent-based programming as modeling and mathematization, with a particular emphasis on designing units of measures (Dickes et al., 2016; Dickes et al., 2020; Sengupta et al., 2018). These phenomenological re-framings are essential for grounding computing in the science classroom in absence of researchers and can help us understand how computational modeling is taken up in a manner that is also relevant to scientific practices, both epistemic and representational.

Overall, we believe that our work illustrates a phenomenological view of re-imagining computing for K12 science requires viewing computing and scientific modeling as complex, heterogeneous, and grounded in practice. For the 4th and 5th-grade science learners in our study, the integration of an agent-based programming and modeling environment for learning kinematics helped them grapple productively with the complexity and uncertainty of their experience of scientific phenomena, which in turn increased the demand for computational abstractions, and at the same time, grounded these abstractions meaningfully in the children's embodied and physical modeling experiences. This, in turn, created contexts where students did more than learn to program: they learned about the inseparable interdependence of modelers and their materials for making meaning of the world, akin to Pickering's (1995) notion of the scientific mangle of practice.

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