

Balancing the Environment: Computational Models as Interactive Participants in a STEM Classroom

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Abstract

This paper describes the work done by sixth grade students to achieve and sustain productive and personally meaningful lines of inquiry with computational models. The capacity to frame interactions with tools as dialogic exchanges with co-participants is a productive practice for disciplinary engagement in science and for computational thinking (Chandrasekharan and Nersessian 2015; Dennett 1989; Latour 1993; Pickering 1995). We propose that computational models have unique affordances for dialogic interaction because they are probabilistic and iteratively executable, features that provide an entry point for students to adopt stances that treat computational models as participants. Our analysis reveals that existing patterns in students' social interactions are resources for interacting flexibly with computational tools as participants. In particular, we found that students treated computational models as participants in three ways: (1) as conversational peers, (2) as co-constructors of lines of inquiry, and (3) as projections of students' agency and identity. Our data also demonstrate that students take on flexible, rather than fixed, stances toward computational participants. These stances parallel scientists' interactions with non-human entities, which often involve treating tools as agentive participants in inquiry (Latour 1999; Pickering 1995), affording students a pathway to practices at the intersection of disciplinary engagement and computational thinking.

Keywords Computational participation · Computational thinking · Agent-based modeling · Science education · Science as practice

Studies of professional science suggest that participation frameworks (Goodwin 2007) should extend to encompass the actions of human and non-human entities (Dennett 1989; Latour 1999). Flexible and dialogic interaction with non-human objects and systems is an important practice in science (Latour 1993; Pickering 1995), particularly when utilizing computational tools (Chandrasekharan and Nersessian 2015). Projecting agency and intentionality onto tools such

as computational models brings into focus their patterns of behavior and inconsistencies, provoking related explanations (Dennett 1989). Therefore, flexibly treating tools as participants in interaction can be productive for disciplinary engagement in science and computational thinking.

In this paper, we propose that computational models have unique affordances for dialogic interaction because they are probabilistic and iteratively executable. Our data suggest that these affordances provide an entry point for students to adopt flexible stances that treat computational models as participants. These relationships with computational models parallel scientists' relationships to objects and systems, affording students a pathway to practices at the intersection of disciplinary engagement and computational thinking. In our analysis, we illustrate how dialogue-inviting affordances of computational models might be leveraged by middle school students, and we identify social resources that support students' engagement with their models as participants in interaction.

More specifically, this paper describes the work done by students to achieve and sustain productive and personally meaningful lines of inquiry with computational models. Using data from a sixth grade STEM classroom engaging in

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computational modeling as part of an NGSS-aligned ecology unit, we analyze different ways that students manage and leverage social interactions with computational models and their human peers. Our analysis reveals that existing patterns in students' social interactions are resources for interacting flexibly with computational tools as participants. Although computational models are not artificially intelligent or literally sapient peers, integrating computational modeling reconfigured the social environment because students *treated* their models as co-participants in inquiry. To analyze the social dynamics that emerged in this classroom, we compare the ways that three students interacted with their computational models and the social world around them. We find that students treated computational models as participants in interaction, moving flexibly between several stances toward their computational models as (1) conversational peers, (2) co-constructors of lines of inquiry, and (3) projections of students' agency and identity. These stances parallel scientists' interactions with non-human entities, which often involve treating tools as agentive participants in inquiry (Latour 1999; Pickering 1995), affording students a pathway to practices at the intersection of disciplinary engagement and computational thinking.

Non-human Participants in Science

Accounts of professional science practice typically focus on the agency of scientists or the scientific community. However, it can be productive, particularly in science, to treat non-human entities, including tools and nature, as participants in inquiry (Dennett 1989; Latour 1993, 1999; Pickering 1995). Broadly, Latour (2005) explains that non-human objects do not act in the same meaningful intentional way that humans do; yet, they are *treated as* participants in action. For example, he argues that it is a fundamentally different activity to hit a nail with and without a hammer, or keep track of inventory with or without a list. While non-human participants do not *determine* the action, these objects might “authorize, allow, afford, encourage, permit, suggest, influence, block, render possible, forbid and so on” (2005 p. 72). Similarly, Dennett (1989) argues attributing intentionality to non-human entities is pervasive and productive. He argues for treating “any object or system whose behavior you want to predict as a rational agent with beliefs and desires” (p. 15). He illustrates this intentional stance by recalling an electrician's explanation of how to protect a water pump from lightning damage: “lightning, he said, always wants to find the best way to the ground, but sometimes it gets tricked into taking second-best paths. You can protect the pump by making another, better path more *obvious* to the lightning” (p. 22). Dennett explains that attributing intentionality to objects and systems supports reasoning about the behavior of objects and systems by

bringing into focus patterns of behavior as well as deviations from those patterns. Attributing beliefs and desires to objects can be particularly productive in science, because this lens focuses explanations on the internal states and process that regulate the behavior of an object or system.

In professional science, Latour demonstrates that non-human entities are often treated as participants in interaction. Latour (1993, 1999) traces Pasteur's many ontological stances toward an entity that he would ultimately call lactic acid fermentation yeast, demonstrating that Pasteur relied on the co-operation of the yeast as a participant in action to understand how to reliably produce fermentation. Similarly, Pickering describes the “dance of agency,” between scientists and the material world. To exemplify this dance, Pickering (1995) describes Glaser's bubble chamber, a tool for experimental elementary-particle physics. Pickering characterizes Glaser's work on the bubble chamber in terms of bursts of activity and periods of passivity, in which Glaser steps back to attend to how nature acts on the machine that he has built. During these periods of material agency, the bubble chamber often performs in unexpected ways. Reconciling these empirical findings with his original ideas shapes Glaser's conjectures and the direction of his research.

These patterns of interaction extend to computational tools in domains that integrate science, engineering, and technology. Studies of emerging fields, such as computational physics (Fox Keller 2003) and bioengineering (Chandrasekharan and Nersessian 2015, 2017), find that scientists treat computational tools as participants in a shared inquiry, even though computational tools do not literally exhibit independent agency. Fox Keller (2003) describes how computational tools are treated as participants in physical science, where computational tools are used to bridge theoretical and empirical methods to explore complex systems for which the underlying dynamics of interaction are relatively unknown. Scientists co-construct theories about these dynamics *with* their models as they run and refine their models. Similarly, Chandrasekharan and Nersessian (2015, 2017) find that bioengineers treat models as participants within distributed cognitive-cultural systems. They explain that computational models take on the role of an external imagination system, producing a close coupling between the scientist's imagination and variations made possible by the computational model. This partnership is more complex than one in which scientists express or externalize their ideas in computational models, because the models support the generation of novel and fine-grained scenarios that would have been impossible to realize in a scientist's mind due to their nuance and complexity. These partnership practices resemble disciplinary engagement in computational sciences, which similarly involves partnering with computational tools in inquiry (Epstein and Axtell 1996; Railsback et al. 2006).

From these studies of professional science, we argue that partnering with computational models is an important skill for

engagement in disciplinary science practices and a significant manifestation of computational thinking. Although computational models do not literally exhibit agency, it is nonetheless important to help students develop flexible strategies of engagement with computation models, including treating computational models as participants in inquiry, given the prevalence of these practices in STEM fields. To prepare K-12 students for the future of work at the human-technology frontier (NSF 2019), it is important to understand how students partner with computational tools in disciplinary settings. Understanding how students construct and navigate human-computational partnerships will inform the design of learning environments that prepare students for success in a landscape with rapid social and technological change.

Computational Models as Participants

A wealth of research demonstrates that computational modeling promotes engagement and conceptual growth in K-12 science. Computational modeling allows students to make representations of key scientific phenomena visible, executable, and interactive, while developing mathematical and domain-specific reasoning skills and supporting deep conceptual understandings of science content (Sengupta et al. 2013; diSessa et al. 1991; Sengupta and Wilensky 2009; Weintrop et al. 2016; Wilensky and Resnick 1999; Wilkerson-Jerde et al. 2015). Engaging in computational modeling can allow students to build deeper understandings of the causal mechanisms underlying phenomena and develop key aspects of computational thinking (Sengupta et al. 2013; Dickes and Sengupta 2013; Papert 1980; Wilensky and Reisman 2006). Computational modeling also provides powerful opportunities for students to participate in computational practices and engage in computational thinking by offering learners new representational infrastructures and new ways of making sense of phenomena and problems (Sengupta et al. 2013; Lee et al. 2011; Weintrop et al. 2016).

But computational modeling can be challenging, for both syntactic and conceptual reasons. Learning environments that combine *visual programming* with *agent-based modeling* (ABM) approaches address both of these barriers (Horn et al. 2014; Sengupta et al. 2015; Guo et al. 2016). On the syntactic side, visual programming environments, where programming is conducted using “blocks” rather than text-based commands (e.g., Scratch, StarLogo Nova), can lower the threshold for engaging in computational modeling. On the conceptual side, ABM approaches can make modeling complex systems accessible to young learners (Brady et al. 2015; Klopfer 2003; Resnick 1994; Wilensky and Reisman 2006) due to the representational correspondence between computational entities (“agents”) and conceptual entities (e.g., particles in a gas model or fish in a pond ecosystem model). ABMs

enable a modeler to “grow” a complex system (Epstein and Axtell 1996) from the interactions between simple constituent components. Modelers do this by identifying agents, giving them computational rules of behavior and interaction, and “running” the system. This enables the computational representation to simulate emergent whole-system behaviors so that the modeler-plus-computer can reason about the agent-level and aggregate-levels of the system.

In this study, we used an ABM environment, StarLogo Nova (SLN), to help students explore population dynamics within an ecosystem. SLN combines a block-based programming environment with a powerful agent-based simulation engine and 3D renderer optimized for modeling complex systems. It also includes the ability to use tables and graphs to gather and visualize data. Although existing research considers the affordances of SLN for learning about complex systems (Yoon et al. 2016, 2017), no prior studies have explored the unique ways that students simultaneously balance and negotiate interactions with SLN computational models as participants, an important link between disciplinary science practices and computational thinking practices. It is important to note that SLN models do not attempt to simulate human interaction, like some computational modeling tools (e.g., *Betty’s Brain*, Leelawong and Biswas 2008) and to recognize that SLN computational models do not exhibit independent agency in a literal sense. Instead, we focus on the relationship between the students and the computational models that they *treat as* participants. This type of relationship more closely mirrors professional science and computational thinking; in professional science, computational tools do not mimic human behavior, yet scientists strategically treat them as participants in inquiry.

In this paper, we describe the work done by sixth grade students to adopt productive stances toward computational models, including stances that treat computational tools as participants in interaction and in inquiry. As described above, flexibly partnering with computational participants is becoming an essential skill within emerging STEM fields. Our data suggest that students leverage existing patterns in social interaction as resources for interacting with computational models as participants in this classroom. From a practical perspective, our data demonstrate that our students interact with their models as conversational peers. The utterances that students produce reflect the intentions and ideas of the students but are also shaped in part by the computational models (Sengupta et al. [forthcoming](#)). In combination with the probabilistic nature of the models and the students’ inexperience with the environment, these participation structures position the models as co-constructors of new lines of inquiry.

To consider the complex social dynamics that occur as students engage with computational models, we use Goodwin’s concept of *interactive footing* (2007). This analytic framework builds from Goffman’s deconstruction of speakers (1981), which parses the interplay between separate voices within an

individual's speech. Goodwin argues that participation frameworks should extend beyond an individual as a speaker to encompass the embodied actions of others who are present and who contribute to achieve communicative acts. In this way, Goodwin attributes utterances to multi-party participants rather than to individual speakers. For example, he describes a conversation involving a participant, Chil, whose vocabulary was limited by a severe stroke. Though Chil is only able to say three words (*yes*, *no*, and *and*), Goodwin describes him as a powerful speaker in interaction because he uses gestures and his limited vocabulary to get others to participate in conversations and co-produce the utterances that he needs.

Although agent-based models and the computational infrastructure that they build upon are not conscious participants in interaction, they encode and express disciplinary perspectives and the intentions of their authors. As such, students' interactions with them exhibit a phenomenon of *co-action* (Moreno-Armella and Brady 2018). In our data, computational models and students interact in complex ways, so that the "utterances"—artifacts, behaviors, and findings—that are produced are projections of the intentions and ideas of the students but are also shaped in part by the computational environment. Like Chil, computational models do not produce complete and meaningful "utterances" on their own, but students cooperate with them to produce speech, and each run of a model acts as a substrate for students' later speech and actions (Goodwin 2017). As we demonstrate in our analysis, students often literally speak to their models, verbalizing questions that they are working to address with their model and attempting to give voice to their models' behaviors and outputs. This form of "conversation" provides support for the notion that students can interact with models as interlocutors in a real sense.

In our study, the students' models also took on an effectively agentive role in their interactions. We conjecture that two features of the models contribute to their effective agency. First, probabilistic behavior is coded into the models, meaning that it is impossible to predict exactly how a model will behave even with full knowledge of the code and the initial parameter settings. This randomness adds nuance to students' interactions with the models, introducing variation even when students are "repeating" a prior run with no change to the code. In this sense, "letting the model speak" in repeated runs reveals more about the behavior of the computational system. Second, this unit was our students' first experience with computational models. Therefore, throughout the unit, we see students actively attempting to make sense of the models' underlying rules for behavior. Our data suggest that these affordances provide any entry point for students to flexibly adopt stances that treat computational models as participants. These relationships to computational models parallel scientists' relationships to objects and systems, affording students a pathway to practices at the intersection of disciplinary engagement and computational thinking.

Methods

This work is part of a five-cycle design study (Cobb et al. 2003) aiming to integrate computational thinking and modeling into an NGSS-aligned curriculum. These data were collected during the pilot implementation of a 9-week ecology unit designed to support students' understanding of the flow of energy and matter in an ecosystem through engagement in a range of model-based inquiry, including diagrammatic, physical, and computational modeling.

Research Context

The current study was conducted in a public middle school located in a small suburban school district in the southeastern United States. According to the state report card, 18% of the school's students qualify for free or reduced lunch. The students are culturally and linguistically diverse: 52% of students identify as White, 25% as Hispanic or Latino, 15% as Black or African American, and 7% as Asian. In addition, 13% of students are classified as English learners. The study was conducted in collaboration with a STEM teacher, Ms. S, who was in her 25th year of teaching. Ms. S's sixth grade STEM class participated in the project (25 students total). All procedures performed in this study were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments. Informed consent and assent were obtained from all individual participants included in the study.

Ms. S and the first author, Ashlyn, co-designed and co-taught all of the lessons for the project. Lessons took place 2 to 3 times a week during the students' 45-min STEM class over the course of approximately 9 weeks, for a total of 22 class sessions. The unit was designed to support standards from the NGSS, including (1) using models to describe that energy in animals' food was once energy from the sun, (2) arguing that plants get the materials they need for growth from air and water, and (3) developing models to describe the movement of matter among plants, animals, decomposers, and the environment (Next Generation Science Standards [NGSS] Lead States 2013).

The unit builds on and refines the SAIL curriculum (NSF DRL#1503330), which is a yearlong science curriculum designed to promote three-dimensional learning as outlined in the NGSS. The curriculum blends science and engineering practices, crosscutting concepts, and disciplinary core ideas to help students explore natural phenomena and design solutions to problems through engineering. The SAIL curriculum was designed to promote language development through purposeful communication (Ellis and Larsen-Freeman 2009; Valdés 2015), drawing on the multiple and diverse channels through which communication occurs (e.g., speech, gesture, drawings, symbols, graphs, and texts). The current study, part

of the larger SAIL+CTM project (NSF DRL#1742138), extends and refines the original SAIL curriculum to integrate computational thinking and modeling. Within the new curriculum, students create computational models in conjunction with physical and diagrammatic models. The physical models enable them to collect and interpret data, and the diagrammatic models fulfill a descriptive and explanatory function (Pierson et al. 2017). Computational models afford students the opportunity to represent unseen or difficult-to-imagine aspects of a phenomenon. They can also be used for speeding up or slowing down time, dealing with hard-to-manage substances; testing and revising ideas about relationships; and running experiments that are dangerous, unethical, or impractical (e.g., studying the spread of forest fires). The ability to translate and coordinate information from multiple modes of modeling (physical, diagrammatic, and computational) is central to both the NGSS (Berland et al. 2015; NGSS Lead States 2013) and computational thinking (Brady et al. 2015; Weintrop et al. 2016).

The SAIL+CTM ecology unit is framed by the driving question, “Why are the salamanders disappearing?” At the beginning of the unit, students watch videos about a local salamander species, demonstrating that the animal, once prevalent in the local environment, is becoming difficult to find. Students generate potential explanations for the decrease in salamanders, beginning with direct causes (e.g., threats to the salamander’s immediate habitat or food source) and expanding throughout the food web and the local environment. The unit is anchored with a simplified computational representation of a food web that includes the salamander, the salamander’s primary prey (isopods), and the isopods’ primary food source (detritus). Students gather information and re-represent the salamanders’ environment with increasing complexity. To learn more about the other organisms in the environment, the students read a modified journal article about the salamanders and create food webs to represent the relationships described in the article. To consider the stability of the environment, they model aquatic habitats with closed-system biodomes that include fish, plants, and snails. Throughout the unit, students refine the original computational models, adding species and attempting to identify stable conditions for the salamanders. Because the implementation of the unit described in this paper was a pilot study, there are many aspects that we plan to change in the following four implementations of the unit. These revisions are not the focus of the current paper; instead, we focus on the students’ interactions with the computational models to inform their integration into this curriculum and to inform other designs to support computational thinking and disciplinary engagement in STEM classrooms.

Computational Modeling Activities

The computational modeling activities in the unit fall into two broad categories: black-box and gray-box modeling

experiences. In the first category, students experience the base model as a “black-box” simulation, interacting with it exclusively through a prepared user interface (see Fig. 1). With sliders, they control the initial populations of salamanders and isopods, as well as the *rate* of inflow of detritus into the system. With buttons, they reset and run the model. With the 3D renderer, they observe the emergent behavior of the ecosystem. Finally, with data boxes, they can see the current size of each population, and with a real-time graph, they can see trends in the sizes of these populations over time. In these activities, students are challenged to keep salamanders alive as long as possible by choosing initial population sizes of salamanders and isopods and by setting the rate of detritus influx.

On day 2 of the project, this challenge is subtly refined through interaction between Ms. S and the students. As the students start on the black-box modeling task, Ms. S asks students, “What do you think you’re trying to do in the environment?” One student responds with “them [the salamanders] not disappearing.” Ms. S says, “Ok, so what needs to happen?” Jeff says, “balance.” Another student, Bruno, adds, “balance the salamanders and isopods.” To clarify, Ms. S asks, “Balance the what?” Several students chorally respond with “the environment.” In this way, the students’ collective understanding of the activity shifts toward a goal of “balancing” the environment, which is then carried through the unit as a goal for students’ physical models (biodomes) and computational models. The base model was designed so that there were many configurations that would support a “balanced” system. Even so, all solutions depend on the supply of detritus, which must be sufficient to sustain a stable population of isopods but not so great as to cause boom-and-crash cycles in the isopod and/or salamander populations.

In later activities, students work with the StarLogo Nova environment as a “gray-box” model. In these activities, students can modify the code for the base model to add species and refine its descriptive power as a model. Work with the model in these activities also involves the students debugging and testing the behavior of their refined models. For instance, over several days, Ms. S shows students how to modify the code of the model to add worms (because the class has learned that salamanders can also eat worms, and worms can eat detritus). Later, some of the students attempt to balance the refined model and consider adding other species to the model. However, not all students were able to add additional species to their models beyond worms during this implementation.

Data Collection and Analysis

Throughout the project, we collected data from a variety of sources to triangulate perspectives of students’ interactions as they were engaging in computational modeling. During each class period, we collected video recordings of the classroom;

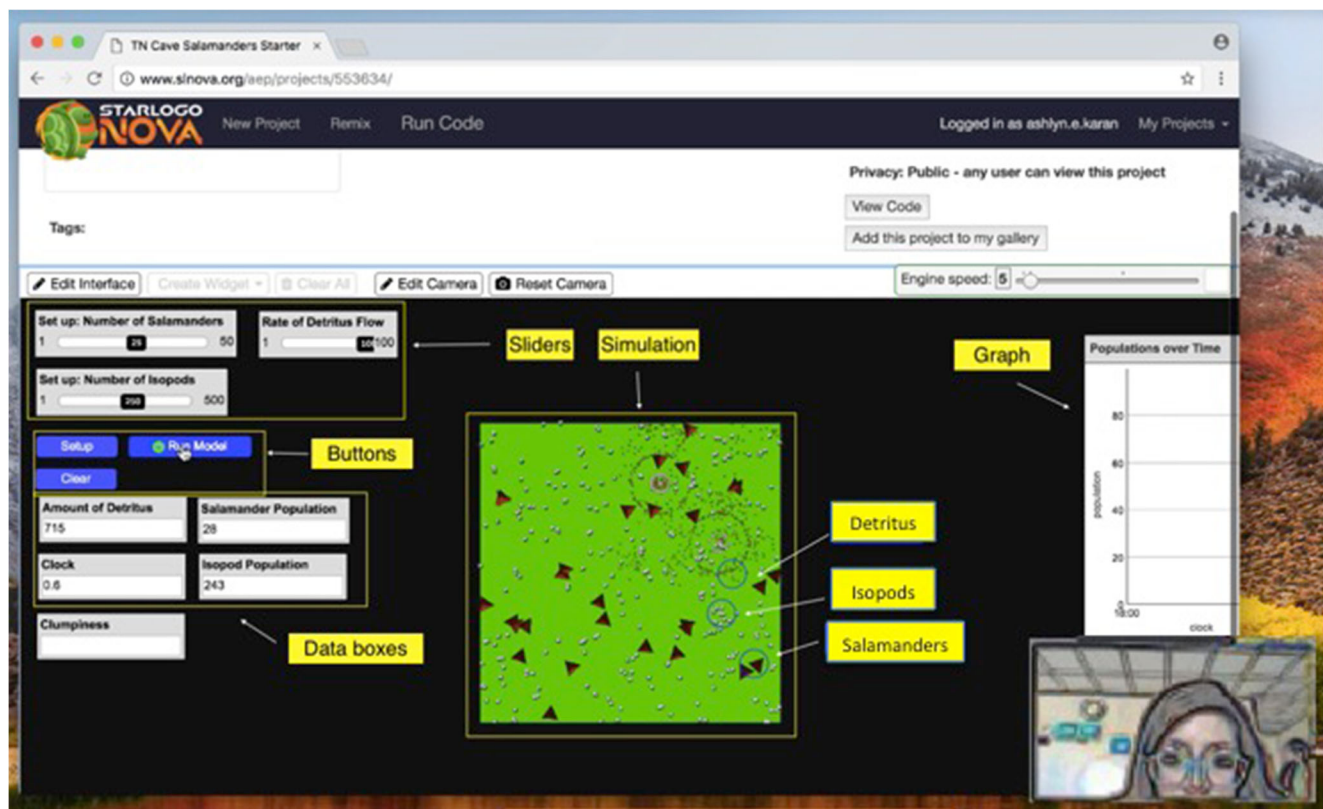


Fig. 1 Black-box interface with purposefully blurred Camtasia video capture of student user in bottom right

audio recordings of Ashlyn’s conversations with students during group and individual work; student artifacts such as models and written reflections; and Ashlyn’s field notes from each class period. In addition, we used Camtasia with three focal students to capture video and audio of the students and their computer screens. The focal students (pseudonyms Camille, Marla, and Garrincha) were selected by the sixth grade teaching team as “typical” students, meaning the teachers felt these students were representative of most students in the sixth grade both academically and behaviorally. At the end of the unit, Ashlyn conducted interviews with each of these three focal students. In the interviews, Ashlyn asked the students about how their computational models related to the other models in the unit, how the students felt about the computational modeling activities (for example, interesting, hard, boring, fun), and how the students perceived social interaction during modeling (for example, whether and what they learned from other students, and whether they prefer working in groups or alone).

To analyze data for this project, we transcribed these interviews and the video recordings of the three focal students interacting with their computational models. Because the students were working on a computational modeling task that involved several streams of visual and quantitative output from the models, discourse and interaction around the models was both interactive and multimodal (Norris and Jones 2005).

Thus, we initially analyzed discourse as units of mediated action. We conceptualized high-level units of mediated action as actions being taken with physical objects (the computational models) and their representations in students’ language. However, through our analysis, we found that the computational models took on a role beyond a mediator of action. Instead, we observed students interacting with their models as participants. We found that our transcripts included utterances co-constructed by both the students and their models. Thus, rather than characterizing our unit of analysis as mediated action, we instead consider units of *co-action* in which both the students and their computational models are participants (Moreno-Armella and Brady 2018).

We draw analytical boundaries in the field of socio-technical activity by building interpretations of articulated intention. Thus, a co-action sequence is grouped by what we, as interpreters of the record, identify as a stable goal. When such a goal is identified, we trace backward to what we perceive to be its roots in the flow of interaction to identify an analytical starting point. When we note this goal-oriented action has played itself out (by the goal’s being achieved, frustrated, altered, or otherwise exhausted), we identify an analytical ending point. Within this delimited time interval, we identify a horizon of action, involving the subset of the social and technical actors in the classroom whose activity is relevant to the unfolding action. Of course, our actors have histories

and memories, and our understanding of these references is limited to our experience and the traces in the data. Our selection of episodes has for this reason favored episodes in which the interactions of present actors have proven sufficient to develop a coherent interpretive theory that is borne out by the subsequent behavior of the actors involved.

To represent the simultaneous co-actions in the transcript, we created *interactive stanzas*, drawing from Gee (2014) and Norris and Jones (2005). While we aim to parse interactions by goals, because students often draw on multiple priorities simultaneously (e.g., social, academic), we have had to make interpretive judgments about the primary goal for each interaction, and we recognize this as a limitation of our analytic approach. We think that this limitation is outweighed by the affordances of the transcript, which allows us to organize overlapping actions while still maintaining the temporal structure of the interactions.

In Table 1, we present an example of our analytic approach. This table is organized into three columns around the simultaneously occurring actions audible in the video. In the left column, Marla interacts with her model while singing in order to identify a stable setup configuration for her isopods. In the analysis section below, we describe how singing creates space for her to interact with her model despite competing activities occurring nearby. In the middle column, Amy announces the stable environment that she has created with her model. She gives voice to output from her model, announcing that her salamanders are “still surviving” even as the model’s clock reaches 165. In the right column, Ms. S and students interact to negotiate access to the lizard that was in the classroom that day.

In our analysis, aligning with prior research (e.g., Farris and Sengupta 2014), we find that interaction with human and computational participants contextualizes and shapes the focal students’ actions. To consider how the focal students manage the worlds of their models and the classroom simultaneously, we analyze their actions in terms of interactive footing,

describing how the students position themselves and others in the flow of activity (Goffman 1981; Goodwin 2007). In this sense, students are “balancing the environment” on two levels: they attempt to balance the environment within the model, but they also balance their interactions with the model and their interactions involving other participants in the classroom.

Analysis and Findings

In this section, we analyze episodes that illustrate the variety of ways that our focal students manage and leverage the ever-changing dynamics of their social interactions with their computational models and their peers. First, we show how Camille interacts with her model as an agentive co-participant in dialogic conversation. Then, we analyze how Marla creates space for engaging with her model by working around the expectations of her teacher and peers without compromising her social connections in the classroom. Finally, we consider how interaction with code and with his friend Bruno bootstraps Garrincha’s engagement in the scientific problems posed by the model.

We see each of these as episodes in which human-human and human-computer interaction dynamics have been achieved that are productive for disciplinary learning. We do not argue that these episodes reflect permanent classes of interaction that are characteristic of these students, these models, or these activities. In fact, in the “[Discussion and Conclusions](#)” section, we include counterpoint examples for each student to demonstrate that these are *not* static modes of interaction. Rather than pointing to robust and repeatable categories of participation, we see these episodes as emergent equilibria: patterns that have appeared in the flow of socio-technological inquiry. We conjecture that these patterns in students’ social interactions are resources for interacting flexibly with computational tools as participants, affording

Table 1 Marla singing to create space for modeling

Marla and computational model	Amy and computational model	Ms. S and students
Marla: {sets isopods to 189} [one]-hundred-eighty-nine ... {clicks <i>Run Model</i> } [one-hundred-eighty]-nine. do do do do do do do boo. ((singing))	Amy: [mine are still surviving.]	Jeff: Ms. S? can I go see the lizard? Ms. S: yes [you may].
Marla: ((singing)) {watching model, sliding the isopod slider up and down, stopping at 345}	Amy: ow . my hair... mine keeps on going it's on one hundred and sixty five.	Ms. S: [um . Betsy you may see the lizard.]
Marla: set up {clicks <i>Clear, Setup, Run Model</i> } come on. ((singing))		
Marla: (((singing)))	Amy: [my salamanders have not died yet. Jeff: good job.]	

students a pathway to practices at the intersection of disciplinary engagement and computational thinking.

Camille: Computational Model as an Agentic Participant

During students' first interaction with the models, on day 2, students are challenged to keep the salamanders alive for as long as possible. Camille approaches this problem by interacting almost exclusively with her model, rarely interacting directly with other students. This is not always the case for Camille; during other class periods, she recruits students from her own table and from other groups to interact with her model. However, because Camille works relatively independently in this episode, it is useful for illustrating how the model can take on the role of a participant in interaction with Camille, moving beyond the role of a tool that mediates her action.

Camille begins interacting with the model before Ms. S has given students directions (see Fig. 2 for a segment of this discourse). As other students find the StarLogo Nova website, Camille clicks *Setup* and *Run Model* for her first run of the model. Camille begins in this example by engaging both with the view of the model in the 3D renderer and with the graph. Almost immediately, her isopod and salamander populations start decreasing. Camille articulates what she sees the model doing, saying aloud, “these are dead” as she circles the simulation with her mouse pointer (02:42). Then, she says, “and they’re decreasing,” as she traces the graph with the mouse pointer (02:44). In this first run, Camille begins by giving voice to the trends produced by the model as it runs. In this way, Camille and the model are co-constructing knowledge about the decrease in salamanders and isopods. Her two observations here are in fact quite profound: Camille and the model are together making connections between agent-level

changes (the deaths of individuals), and aggregate-level changes (trends in the populations). As noise around her increases, Camille starts to sing while tracing the graph, distancing herself from ambient human-human interactions in the classroom to create an isolated space for herself to focus on interacting with the model (03:02).

During Run 2 of the model, Ms. S speaks to the whole class and asks students to click *Clear*, *Setup*, and *Run Model*. She facilitates a discussion about how to manipulate the sliders in the model and about the students' objective in this activity (balancing the environment). Throughout this discussion, Camille works to maintain her isolated workspace, giving voice to data from the data boxes and the graph in her model as she traces the lines on the graph with her mouse pointer. For example, as Ms. S is describing the assignment, Camille reports in a whisper the number of salamanders in her model: “eighteen salamanders . twenty . . twenty-three . twenty-four . eight . nine . twenty-nine” (04:24). A few minutes later, when her model crashes, Camille uses her mouse pointer to trace the salamanders' line on the graph, reporting, “they’re literally gone” (05:48). As she did during the first run of the model, Camille creates an audio-visual space for interaction with the model despite all of the commotion around her.

As Camille interacts with the model, her speech becomes more conversational (see Fig. 3). In Run 3, she reports on data from the graph (08:01), but then expresses disappointment when the salamanders die (08:18). In response, she sets all of her sliders to 1, but then catches herself, saying “wait if I do that—” (08:36). She interrupts herself and resets the sliders. She presses *Run Model*, but there is not feedback from the model, so she says “hold on . set up,” as if she is asking the model to wait for her to press the *Setup* button (08:55). During Run 5, she sets all the sliders to 1 and tells the single salamander in the model that it’s “gonna die” (09:06). When it does, she tries a new set up configuration for Run 6. In addition to

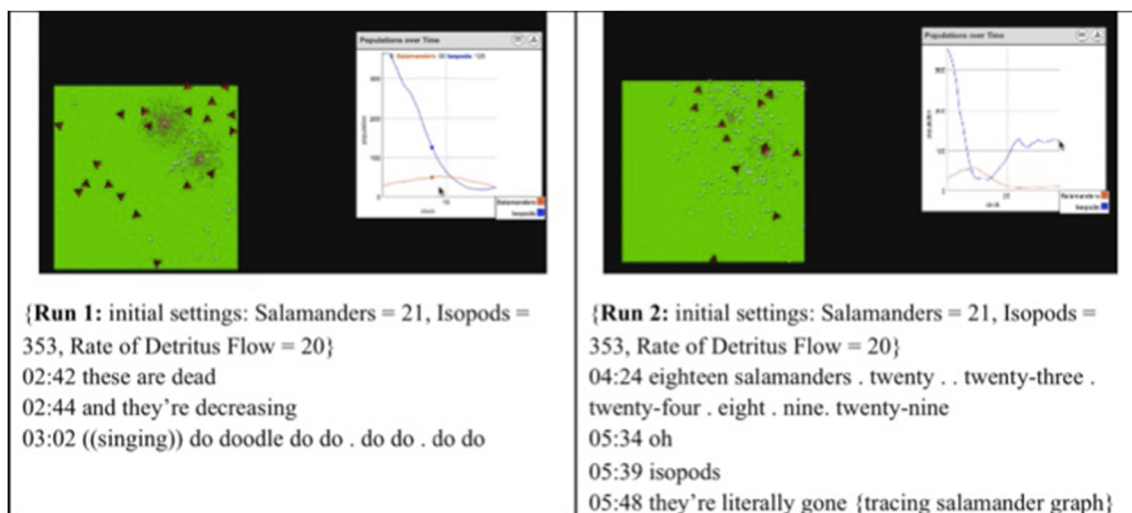


Fig. 2 Camille's articulates her model's action

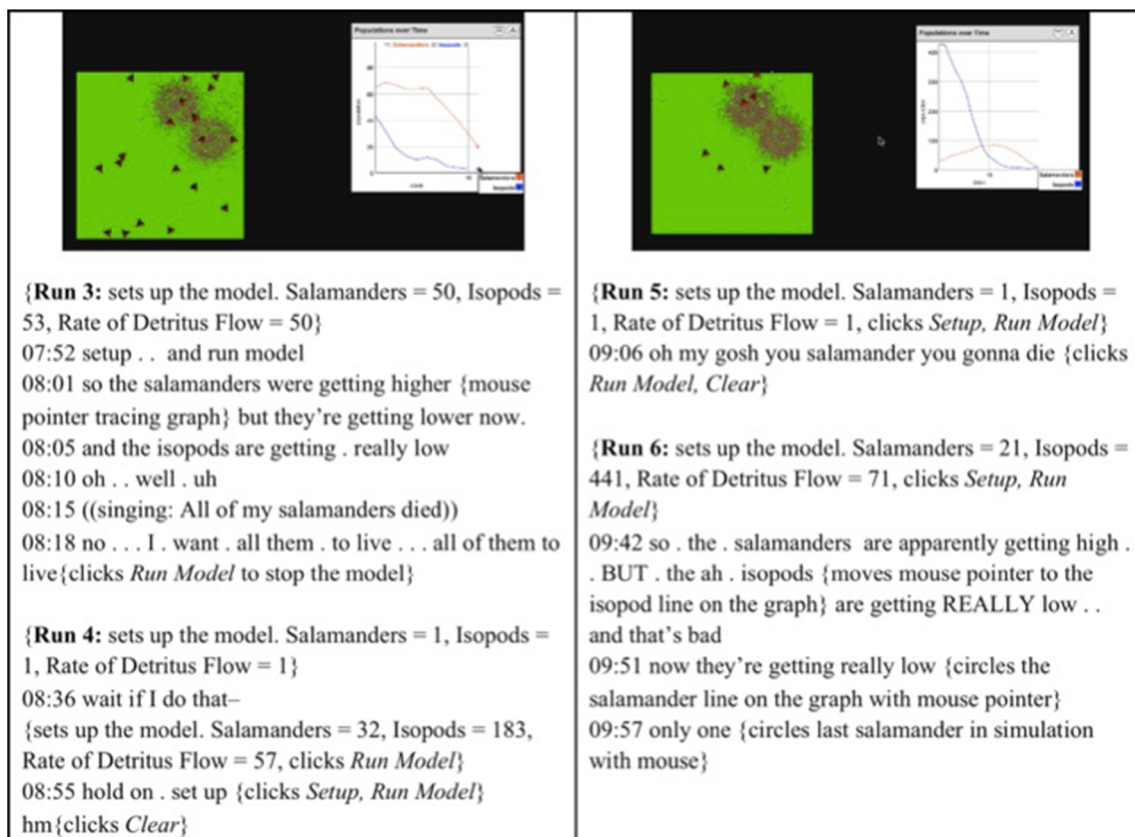


Fig. 3 Camille converses with her model

reporting data, as she did in early runs, she now begins to interpret data and judge outputs. For example, when she notices that the isopods are getting low, she says, “that’s bad” (09:42).

Later in the class period, Camille directly addresses the computational model using a variety of forms of speech, interacting with the model increasingly in the manner of a socially challenging peer. For instance, as the model crashes in Run 7, she says to the model in a sharp staccato tone, “I do not know!” and then asks, “what are you doing?” She bargains with the agents in the model, softening and lowering her voice and asking “can you like . stay alive please?” This speech resembles a challenging interaction with a peer. First, Camille expresses frustration, and, seeing no change in the trend of decreasing salamanders, makes a plea for cooperation.

In addition to negotiating with the model broadly, at other times, Camille speaks directly to agents in the model. In Run 9, she sets up the model with 1 salamander, 1 isopod, and 100 for the rate of detritus flow. As the isopods dramatically increase in the model, the single salamander wanders in a corner of the screen opposite the isopods. She narrates this moment by singing “Dun dun dun .. dun dun dun” with a dramatic tone and in a minor key. Once the salamander reaches the isopods and rapidly reproduces, she sings, “the salamanders are in-

crea-sing . . in-crea-sing.” Then, she speaks to the isopods directly, warning with a deep voice, “they’re taking over.” This is loud enough to attract the attention of other students. Adam looks over at Camille’s model and exclaims, “wow you have one hundred salamanders almost . . . dang.” Camille does not respond to Adam. Instead, she continues with the dramatic low voice, warning the isopods, “they’re switching over . . they’re taking over the land . . everybody RUN.” During this run, Camille continues to prioritize the model over her peers in interaction, speaking to the agents, dramatizing their interactions, and interpreting, rather than simply re-voicing, the data she observes.

During Run 10, Camille speaks to the model as if she and the model are collectively working to solve a problem, using phrases like, “let’s see what’s . . isopods” as she is adjusting the slider for isopods. For the salamanders, she says, “let’s do two this time.” This speech resembles the collaborative interaction we might expect from a pair of students working together. Instead of using singular pronouns, she uses the plural “let’s.” In this way, Camille makes suggestions for the model rather than announcing her next action to the computer. Thus, as Camille engages with the model throughout the class period, her interactions with the model shift to position the model as an interlocutor and as a co-participant in the goal-directed inquiry of the activity. At the beginning of the class, she re-

voices its behavior, reading data from the model out loud; but by the end of class, she has co-constructed a dialogue with the model and with the agents within the model.

Contrasting these participation structures provides a lens for considering how Camille perceives her interactions with the computational model. When Camille reports data from the screen, she uses declarative phrases to announce the output from the data boxes or the graph. With these utterances, Camille signals that the model is communicating with her, but she does not directly address the model with her speech. This structure shifts throughout the class period. Later in the class, Camille tries on new participation structures, speaking directly to the model and collaborating with the model as though with a partner. For example, during Run 7, Camille speaks to the model as an uncooperative peer, expressing frustration and negotiating with the agents in the model. During Run 10, she speaks to the model as a partner, using words like “let’s” to suggest initial configurations for the sliders. Camille also speaks directly to the model in Run 9, although her role is slightly different during this run. Rather than speaking to the model as a peer, she contributes to the narrative playing out in the model’s 3D renderer by creating dramatic music and warning the isopods about the threat of the salamanders.

All of these runs occurred within 15 min, yet in this short amount of time, Camille engaged with the model using a wide range of interactive footings that shifted and evolved as she interacted with the model. This variation suggests that analyzing students’ computational modeling practices solely from a lens of human-tool interaction could look past students’ tendencies to interact with computational models as participants in disciplinary settings and, in turn, overlook opportunities to capitalize on students’ stances with respect to their computational models for science learning and for cultivating computational thinking practices.

Marla: Managing Social Interaction and Computational Modeling

Whereas Camille distances herself from her peers in the example above, Marla attempts on the same day to balance participation with her model and with her peers. Like Camille, Marla at times creates space for modeling by singing or by re-voicing data from her model. Yet, at other times, Marla simultaneously interacts with her model and with other human participants in the room. With our analysis in this section, we present an example of how a student might balance the social world of the classroom with a systematic investigation of a computational model, leveraging social resources to negotiate interactions with human and computational peers.

Marla relies on a variety of epistemic and social resources for exploring her model, including explicitly stating and testing conjectures. For example, in Marla’s first run of the model, she moves each slider to halfway between the minimum and

maximum value, saying, “this is half of each number.” In the context of Marla’s goal to create a balanced environment, this statement can be interpreted as a conjecture that setting each parameter to “half” will support a balanced environment. In her next run, she conjectures, “wait the detritus flow is better when it’s . higher” as she increases the rate of detritus flow. She adjusts the slider and says, “there . that should be good.” These explicit conjectures help Marla systematically explore the model by expressing a hypothesis prior to each run.

The practice of defining explicit conjectures before each run may help Marla recognize unanticipated outputs from her model as she tests her conjectures. As Marla observes her model, she often expresses surprise or asks questions of her model (see her facial expression in Fig. 4a). During this run, Marla has intended to increase the rate of detritus flow, yet she seems shocked by the drastic increase in detritus on the screen, gasping with surprise and saying, “look how many!” Typically, after Marla expresses surprise or asks questions of her model, she revises her conjectures. For example, in this case, Marla says, “I don’t think it needs to be 100 maybe like – 35?” and moves the detritus slider down to 35. These data suggest that the practice of explicitly stating and evaluating her conjectures supports systematic exploration of the model, allowing Marla to use previous runs to inform future runs.

In addition to epistemic resources for exploring the model, Marla also draws on social resources to interpret the model. She frequently turns her screen toward Amy, who sits next to her, to show her what is happening in her model. Marla and Amy use talk and gesture to interpret the model. For example, after setting the rate of detritus flow to 100, Marla turns the model toward Amy, saying “wait look how much the detritus is coming” and pointing to the screen. Amy responds, “that’s a lot it’s like making little two circles.” Marla says “it’s like—” and gestures to mimic the circular waves of detritus dispersion. This interaction is focused entirely on the model, but at other times, the students talk about the models and their lives out of school simultaneously. For example, during one run, Marla’s model nearly crashes. As the isopods and salamanders increase, she turns the computer toward Amy and says “oh this is cool . look . it just re-started.” Jeff, sitting across from Marla, responds with a joke: “your mom re-started.” Amy and Marla both look toward Jeff as Amy says, “Yeah – so she’s young again?” Marla looks back down to her model and notices that it is crashing, saying in a softer voice, “that looks wrong.” Amy, still speaking to Jeff, says “that’s good.” Once the model crashes, Marla re-joins the social conversation, contributing “my mom works out five days a week.” In this moment, social interaction blends seamlessly with academic interaction centered on the model.

Marla uses several strategies to negotiate social interaction while attempting to create a balanced environment in her model. In some cases, Marla engages in social interaction while simultaneously creating space for modeling. For example, she

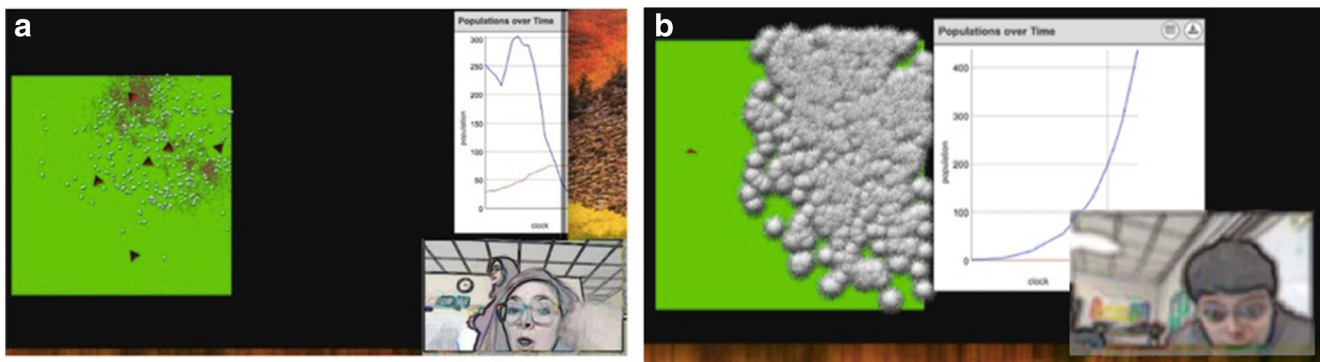


Fig. 4 Students are surprised by outcomes of their models (**a**—left) Between gasps, Marla says, “look how many,” in response to the increase in detritus. (**b**—right) Garrincha exclaims “Oh my – expanding bro!”

is obligated to interact with her teacher even when she is focused on her model. Below, Ms. S explicitly asks Marla if she has seen the lizard in the classroom that day:

Ms. S: ok good. have you seen it Marla?
 Marla: {moves sliders toward 40} umm . . have I s- seen what?
 Ms. S: have you seen [my lizard?]
 Marla:[no.] {shakes head, continues to move the sliders}

In this interaction, although Marla engages with Ms. S, she seems to violate Ms. S’s expectation that Marla will disengage with the model to go see the lizard. Marla complies with her teacher by participating in the interaction, but she seems primarily focused on her model. She does not initially understand what Ms. S means by “it,” but slowly and hesitantly clarifies as she continues to set up her model. Once Marla realizes that “it” refers to the lizard, she interrupts Ms. S with a “no” before Ms. S finishes her sentence, and she then continues to work on her model. In this way, Marla negotiates the interaction with her teacher in a way that creates space for modeling.

Marla uses this strategy when interacting with peers as well. On several occasions, Marla jokes with the other students at her table (Amy and Jeff) while simultaneously attending to her model. These interactions typically occur when Marla’s model is already running. For example, Marla is willing to engage with Jeff’s joke (“your mom re-started,” described above) as her model is running. At other times, particularly when she is setting up her model or appears confused by the model’s outcome, Marla shifts her footing to “check out” socially from interactions with others in a way that creates space for interacting with her model. In these situations, Marla does not respond to her teacher’s or peers’ direct or indirect bids to recruit her into their activities, violating their expectation that Marla will participate in their interactions. In the example below, Marla does not respond to her teacher’s directions or Amy’s questions, and instead, continues to interact with her model.

Ms. S: bookmark if you’re not sure how? Um I usually drag it all to the bar you can do it however you want just make sure you save everything.

Amy: bookmarked. . . do you need to bookmark it?

Marla: {moves detritus slider to 1}

Amy: ow my hair’s . . ow . . . click that little [star]

Marla: [wait the] detritus flow is better when it’s . higher {moves detritus slider to 100}

In this interaction, Marla positions herself as outside of the human-human interaction despite Amy’s bids to involve her. Instead, Marla engages only in human-computer interaction with her model, responding to the model by suggesting that the “detritus flow is better when it’s higher.”

In other contexts, Marla creates a separate space to work with her model by humming or singing. At times she sings the numbers on her screen or sings syllables as placeholders. Several interpretations are possible: she could be distancing herself from nearby human-human interactions by signaling that she is focused on her model, or she could be creating an individual soundscape that prevents her from overhearing others’ interactions. The singing and humming often occur when there is a lot of noise happening around her or when others make bids for her attention. We presented an example in Table 1 earlier. In that interaction, Amy is announcing her success with her model, aiming for recognition from the teacher or her peers. At the same time, Ms. S is managing access to the lizard in the classroom. Marla seems to be creating a workspace by establishing a barrier between herself and these human-human interactions by singing, allowing her to focus on interactions with her model in a busy classroom.

While the transcript in Table 1 presents social interaction as potentially distracting, Amy’s repeated bids for recognition ultimately support Marla in balancing her own model. After Jeff acknowledges Amy (“good job”), Amy continues to report success. Eventually, Amy frames her accomplishment as a rule for balancing the model. She says “mine have the same . the same amount. mine are 400-400-400 . . . you can do 50-50-50 or whatever number you want.” Marla takes up this suggestion

as a conjecture, setting each of her sliders to 11. She announces that she “figured it out” even before she observes the outcome of this run of the model. Despite Marla’s confidence, the model crashes. In response, the girls jointly revise the conjecture; Marla suggests, “I think it has to be 40-40-40.”

In summary, if we only attend to Marla’s interaction with the model, we are missing the work she is doing to create space for herself to interact with her model while leveraging social and academic interactions with her peers for a variety of goals. In designing learning environments for computational modeling, it is therefore critical to consider scaffolding not only for engagement with the model but also to create space for productive interaction and collaboration with, as well as distance from, the other participants in the classroom. In our analysis of Marla’s interaction with her model and her peers, we see how she sustains the fragile thread of inquiry, maintaining continuity across her conjectures. At times, she reaches out into the noisy environment to garner resources and feedback necessary to her work, but in doing so, must simultaneously manage the complex social dynamics of the classroom. These skills are necessary for success in a classroom environment, yet may not be skills that can be scaffolded in a generic way given the wide range of learners in any classroom. Whereas Camille’s focal example provides a lens for how a student could interact with a model on her own, Marla’s example provides a lens for how a student could manage and balance social interaction with inquiry. Next, we will present an example in which social interaction serves as a jumping-off point for inquiry with the computational model.

Garrincha: Interaction with the Computer and with a Peer Facilitates Inquiry

On the first day with the computational models, like Camille, Garrincha rarely interacted with other students. Although he was compliant with classroom expectations in terms of interaction with the model, he rarely asked questions or expressed excitement. In this section, we illustrate how Garrincha later enthusiastically reframed and investigated the problem of how to balance the environment in his computational model. We show how two factors led him back to the problem of balancing the environment: interacting with the code blocks and interacting with his friend Bruno, who had been moved next to Garrincha a few days earlier. The coding objective for the day and social interaction with Bruno seem like they might steer Garrincha *away* from attempting to balance the environment. Yet, these interactions engage Garrincha enthusiastically in this initial domain-specific question.

In this section, we draw from data collected during students’ introduction to the code behind the model that they had manipulated previously as a black-box simulation. In designing this activity, we chose to show students how to change features of blocks in the base model (like assigning drop-down or

numerical values for variables) before they moved new blocks into or out of the code. This allowed students to connect the code to implications for their models. It also minimized frustration and confusion during their first interaction with code because the students had fewer opportunities to misplace blocks and create unintended bugs. During this lesson, we encouraged students to change the size, shape, and color of the isopods in their models. Because these are primarily esthetic features of the model, we did not expect the activity to lead back to questions about balancing the environment. Rather, our goal was to build a foundation for students to understand the relationship between the blocks and the model and to build their confidence with changing code in the model. Thus, it is surprising that interacting with the model in this way leads Garrincha and Bruno back to questions about balancing the environment.

At the beginning of the activity, Ms. S demonstrates how to change isopods’ size. Garrincha and Bruno follow along, but also joke with each other. For example, after Ms. S shows how to make the isopods larger (“so press *Set Up* . . . OH yeah they’re bigger”), Garrincha turns to Bruno and whispers, “that’s what she said.” Both of the boys laugh as they set their isopods to size 11. The boys’ affective engagement shifts as they see the impact of changing the code in their own models. The boys are visibly surprised by the dramatic change in the isopods. Bruno repeatedly asks both Ashlyn and Ms. S “wait why are they so big?” With wide eyes, Garrincha leans into his computer and exclaims “Oh my – expanding bro!” (see Fig. 4b). Although the boys were replicating a change that Ms. S had demonstrated, it seems that interacting with their own models leads to a different type of engagement.

Next, Ms. S demonstrates changing the shape of the isopods, which were originally set to “urchin.” Ms. S says, “now this time . remember we talked about the urchins? . . . why don’t we change it and I’m gonna let Amy choose . whatever she wants, so click on . . . there’s a drop down that will happen . . . you guys choose whatever you want.” Betsy asks, “can we choose the color too?” Ms. S responds, “if you want to change the color you can as well.” Previously, during this class period, when Ms. S stopped the students for instruction, Garrincha turned away from his model and toward the board. However, at this point, Garrincha and Bruno break away from the rest of the class’ interaction and continue to make changes to their models. Ms. S asks several students what button they need to push after they make changes to their model (they need to push *Run Code* to compile their changes, which students often forget). Meanwhile, Bruno and Garrincha whisper excitedly about what shapes they might use, switching as they confer between English and the Spanish that they share. For example:

Garrincha: I put a . . . I turned it into a shark what did you do?

Bruno: nothing . . . I still haven’t entered it . . . they have *leones*? Lionel Messi

In this conversation, Garrincha and Bruno connect their models to their out-of-school interests; the lions in the model remind Bruno of a professional soccer player (Lionel Messi). The boys' whispered conversation builds interest in the activity, but it also slows them down. Garrincha is briefly halted by the error Ms. S was trying to address with the whole-class conversation. In his code, Garrincha had changed the isopods' color to green and shape to dragon, but when he clicks *Setup* and *Run Model* the isopods still look like white urchins. He says, "how come it doesn't go," and scrolls back down to the code. Bruno helps him by prompting, "run code."

Both boys are excited about the new shapes of their isopods. Bruno exclaims "*tiburones!*" in a high-pitched voice. Garrincha laughs and asks, "Is it really sharks?" He smiles and announces, "ah there's dragons for me!" The boys go back and forth, each insisting the other look at his screen; for example, Bruno says, "no but look at mine look at mine." The boys even recruit friends at other tables to see their models. This new attachment to the isopods affects how the boys approach the problem of balancing the environment. Whereas their initial engagement with the task of balancing the environment seemed grounded in compliance, they now express concern about the isopods.

Garrincha turns his isopods into sharks and tries to show his friend Jason, but the sharks quickly die. Garrincha leans in and expresses despair about the loss of his shark-isopods, whereas he was previously silent when his isopod population crashed (day 2). This time, as he watches the shark-isopods decrease, he says, "they're missing they're gone they're gone!" Bruno asks, "they are sharks right?" Garrincha responds "yeah . . . what do they eat?" Bruno points to the screen and says "it's those . . . those guys." Garrincha challenges his claim: "but I don't see that . . . that they're eating them." This interaction suggests that Garrincha's new interest in the isopods as a result of changing their traits spurs questions about the food web in the model in service of keeping the shark-isopods alive.

As the boys continue to change the shapes of the isopods in their models, Garrincha has more questions about the factors that affect the isopods' survival. He changes the isopod shape to "lion," and asks "Why do the lions m—like they die quickly." Then he tries pyramids and asks, "the . the . they die quick why do they – if you put something else instead of the urchin why do they die fast?" Ashlyn is nearby and responds, "I don't know um are the – are the other things different size than the urchins?" Garrincha says, "I put pyramids they're dying quickly." It is unclear whether Garrincha is considering size as a factor for isopod survival, because he is interrupted by Bruno. Garrincha and Bruno consider color as a factor in the disappearance of Bruno's isopods. Garrincha suggests that Bruno's isopods are dying, "maybe cause you put the color red." This interaction suggests that the boys are concerned about the survival of their isopods and that they are considering factors beyond shape in their survival.

When Garrincha turns back to his own model, he notices that, "you can put letters too" for the shape of the isopods (see Fig. 5, 35:46). He chooses "B" and shows Bruno, who says "oh B – B for my name Bruno" (36:01). Garrincha runs the model and reports to Bruno, "you're dying . . . you're dying! . . . you died" (36:07). At this point, Ms. S calls the students back to give more directions, so Garrincha and Bruno end their conversation. However, Garrincha does not stop interacting with his model. He changes the isopods to "G" for Garrincha (36:52). He changes the color from yellow to turquoise, perhaps to better camouflage the isopods, since earlier he proposed that Bruno's isopods might have been dying because of their red color. He also reduces the isopods' size from 11 to 2, bringing them down to their original size, potentially drawing from Ashlyn's prompt to consider size a few minutes before. Still, the isopods do not thrive, and Garrincha whispers to the computer "they're eating me" (37:21). In response, Garrincha goes back to the strategy from the first day with the models: manipulating the sliders (37:29). He moves the number of salamanders from 21 down to 7, and he increases the isopods from 353 to 500. Then, he runs the model to see if his isopods survive. He whispers, "I got it" as his isopod population increases (37:38).

This example reaffirms findings from prior research that demonstrate that "thinking like" the agents in a computational model supports students' understanding of scientific phenomena by helping students connect agent-level actions and interactions to emergent aggregate level patterns or trends (Wilensky and Reisman 2006; Wilensky and Resnick 1999). Becoming increasingly "identified with" and "inhabiting" the agents in turn drives engagement for Garrincha, increasing his attention to details in the model, such as what the agents eat and how the agents' traits impact their survival. In this example, Garrincha fluidly moves between the perspective of an observer of the model (e.g., "I got it" 37:38) and an isopod (e.g., "they're eating me" 37:21). This "fusion" of identity and agency between symbols and referents facilitates thinking across agent and aggregate levels (Nemirovsky et al. 1998).

In summary, the computational model provides a means by which Garrincha and Bruno are able to return to their original line inquiry, balancing the environment. Both Bruno and the model act as peers for Garrincha with key roles as co-participants in constructing knowledge about balancing the environment. Because the isopods took on the shapes of things that mattered to Garrincha and Bruno, the students became newly invested in the isopods' survival. They explored a range of factors that could contribute to their survival, including size, shape, color, and the setup configurations that they attempted to balance during their initial interaction with the computational models. The model also acted as a participant in these interactions, challenging the boys' assumptions about what mattered for the survival of agents in their models. On the first day with the models, the boys did not consider the traits of the isopods, yet the surprising outcomes that the

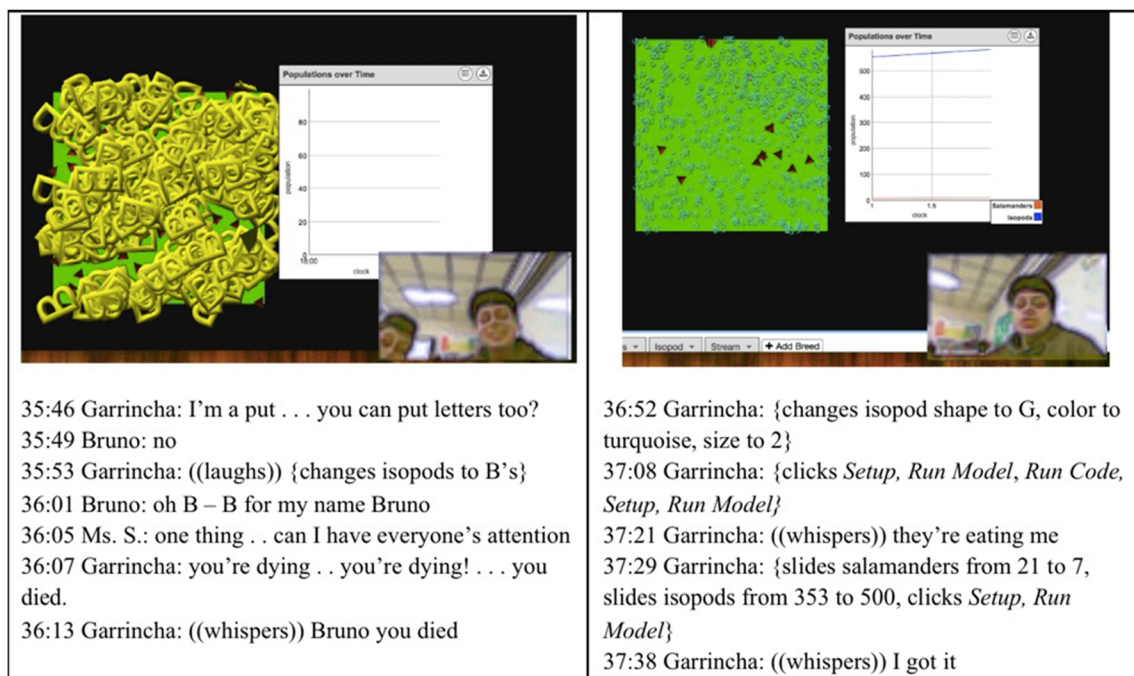


Fig. 5 Garrincha changes the isopods' shape to B (for Bruno) and G (for Garrincha)

models produce as the boys change these traits lead the boys to co-construct new lines of inquiry with their models. In addition, affordances of the agent-based modeling environment enable Garrincha and Bruno to project their identities into the model, allowing them to “dive in” and “step back” between the agent and aggregate levels of the model (Ackermann 2012). Projecting into the model in this way goes beyond using the model as a tool and instead frames the model as a co-participant in interaction.

It is impossible to parse to what extent interaction with the code versus interaction with Bruno contributed to Garrincha's interest in balancing the environment. It is possible that if the boys had been sitting near each other on the first day, they would have co-constructed a narrative about the isopods that was equally compelling to them and that facilitated engagement with the task of balancing the environment. It is also possible that even if Garrincha were not sitting next to Bruno as he learned how to change the isopods' traits, he would have become equally as invested in the isopods' survival. Yet, in these data and in classrooms more broadly, interactions with computational models and with other students seem inextricably connected. Thus, it is important to consider the constellation of computational and peer interactions that could be leveraged to support learning in classroom contexts.

Discussion and Conclusions

Flexible and dialogic interaction with non-human objects and systems is important for disciplinary engagement in

science (Latour 1993; Pickering 1995), computational thinking (Epstein and Axtell 1996; Railsback et al. 2006), and success at the human-technology frontier (Chandrasekharan and Nersessian 2015, 2017; Fox Keller 2003). Projecting agency and intentionality onto tools such as computational models brings into focus their patterns of behavior and inconsistencies, provoking related explanations (Dennett 1989). In the analysis above, we describe the work done by three students to achieve and sustain productive and personally meaningful lines of inquiry in a learning environment populated by various computational and human participants and various opportunities for interaction with these participants. The analysis suggests that computational models have unique affordances for engaging students in dialogic interaction because they are probabilistic and iteratively executable, affording opportunities for students to interact with models as (1) conversational peers, (2) co-constructors of lines of inquiry, and (3) projections of students' agency and identity. Furthermore, our analysis above reveals that existing patterns in students' social interactions are resources for interacting flexibly with computational tools as participants, and thus are resources for cultivating this important practice for disciplinary engagement in science and in computational thinking. At the same time, our data demonstrate that participation structures and students' strategies for engaging in inquiry are constantly in flux. In this section, we elaborate on these conclusions and identify directions for future research based on the findings and limitations of this study.

Reframing Computational Participation to Include Computers as Participants

In response to our data, we propose extending the concept of “computational participation” (Burke et al. 2016; Kafai and Burke 2013) to include computational agents as participants in the interaction. Computational participation acknowledges that code is not created in a vacuum, but rather as a means for sharing and connecting with others. Burke and colleagues explain (Burke et al. 2016 p. 373): “Whereas computational thinking uses an algorithmic lens toward problem solving, computational participation extends this thinking beyond the individual to integrate social networks and digital tools in a networked society.” Our examples illustrate the importance and power of participating in social networks around coding. Yet, our data also suggest that computational agents can act as more than tools to be leveraged by social networks—from the students’ perspective, computational agents can themselves become participants in interaction. Expanding computational participation to include computational entities recognizes that it requires skill and judgment to adjust one’s footing strategically toward computers to position them productively as co-participants. This skill lies at the intersection of disciplinary engagement and computational thinking.

In this classroom, computers are treated as participants in three ways: (1) as conversational peers, (2) as co-constructors of lines of inquiry, and (3) as projections of students’ agency and identity. We argue that these stances toward computational models are productive for disciplinary engagement and computational thinking because they parallel the ways that scientists flexibly engage with tools as participants. Stabilizing these stances as part of a classroom’s accepted norms and routines requires an appreciation of how they can be deliberately utilized by learners to bring about specific relations between humans and computers and to yield desired results. Following from Sengupta et al. (2018) proposal that computational thinking in STEM should be viewed phenomenologically, future research should explore how students’ heterogeneous stances toward computational models become stabilized over time.

We saw evidence of computational models acting as conversational peers across the examples from all three focal students, although the students partnered with their models in different ways. For example, Camille and Marla adopted an *intentional stance* toward their models (Dennett 1989) as they spoke directly to their models. Both girls re-voiced data from their models, expressed conjectures, and asked questions of their models (e.g., “I don’t think it needs to be 100 maybe like – 35?” from Marla, and “let’s do two [salamanders] this time” from Camille). In the examples analyzed above, Camille strived to engage with her model one-on-one, to the exclusion of interactions with human peers. In contrast, Marla seamlessly integrated interactions with her model and interactions with

other students. Yet, both girls directly addressed their computational models in their speech, suggesting that they saw their models as participants in interaction.

The register that the girls used with their models further suggests that they saw their models not only as co-participants but also as peers. When Marla and Camille talked to adults, like Ms. S or Ashlyn, they used a formal register, speaking in complete sentences and using a calm even tone. For example, on day 2, when Ashlyn asked Marla what she was learning from her model, Marla said, “It could be better for the salamanders if all of the other elements of the habitat were the same amount as the salamanders so they are even.” In contrast, when Marla spoke to her model, her speech was fragmented and her tone was more emotional, approximating her speech patterns with fellow students. With her model, she issued imperative commands (“stop running . . . I said stop running!”), asked questions (“Wait how do we have – ?”), and provided encouragement (“Come on!”). Marla used this informal register even though she knew that the camera and microphone on the computer were recording her speech and actions and that an adult could watch the recording later. Camille also used an informal register with her model, conversing with it as she might with an uncooperative peer (Run 7) or partner (Run 10). This informal register suggests that the girls saw their models as peers and compatriots rather than as sources of adult authority. Similarly, studies of professional science suggest that scientists also engage with computational tools as peers, describing scientists “partnering” with agent-based computational models (Epstein and Axtell 1996; Railsback et al. 2006).

Although Garrincha does not explicitly speak to his model, his example highlights another way that the computational models can act as participants in students’ interactions. Garrincha and Bruno co-constructed new lines of inquiry with their models as their models produced surprising output. Marla and Camille also responded generatively to surprises from their models. For example, Marla was shocked by a dramatic increase in detritus (Fig. 4a) leading her to new conjectures about its role in the food web. Similarly, Camille was surprised that all of the salamanders died in Run 3 (Fig. 3), and in the next run, she reversed the setup configuration for salamanders. These dialogic interactions with their models parallel the *dance of agency* that Pickering (1995) describes between scientists and material supports for their research. Experiences of surprise depend on and promote a dialogic, dance-like relationship with the computer as a partner in students’ investigation. The rapidly mutable and executable features of the model also afforded an *external imagination*, expanding the variations and nuances that students were able to explore (Chandrasekharan and Nersessian 2015, 2017).

In addition, the computational models acted as participants as the students projected their identities into their models in various ways that furthered their inquiry. This is most explicit

in Garrincha's example, where he used letters to connect the isopods to himself and Bruno. When the B-isopods were decreasing, he said, "*you* died" to Bruno. When the G-isopods died, he said, "*they're* eating *me*." This connection projected the boys into the model, positioning the model as a participant that was inextricably linked to Garrincha and Bruno. Similarly, Camille projected agency and identity into the model when she spoke directly to agents, warning the isopods to run away from the salamanders. In this way, the students projected themselves into the model, moving beyond using the model as a tool and instead framing their models and the agents within them as co-participants in interaction. Similar affective engagement with non-human entities exists in professional science practice (Fox Keller 1983; Salk 1983). For example, Jonas Salk describes affectively projecting into the systems he studied: "When I observed phenomena in the laboratory that I did not understand, I would also ask questions as if interrogating myself: 'Why would I do that if I were a virus or a cancer cell, or the immune system?'" Before long, this internal dialogue became second nature to me; I found that my mind worked this way all the time" (Salk 1983, p. 7).

In this context, our data suggest that integrating disciplinary engagement with computational thinking involved knowing how to partner with computational agents as participants rather than simply as tools. This is a shift from the historical human-centric perspectives on computational thinking. Computational thinking often describes coding as formatting problems in ways that can be solved by a computer (e.g., Wing 2008), and computational participation characterizes coding as a way of sharing and connecting with others in the practices of the discipline (e.g., Burke 2016). We propose a new perspective that includes knowing how to structure one's engagement with a computer flexibly, including the ability to adopt a stance that treats a computer not merely as a tool for solving problems but as a peer with whom one can collaborate to generate and pursue new lines of inquiry. This perspective aligns with practices observed in emerging STEM fields, in which computational partners are treated as participants in inquiry (Chandrasekharan and Nersessian 2015, 2017; Epstein and Axtell 1996; Fox Keller 2003; Railsback et al. 2006).

Social Dynamics Among Humans and Computers Are Constantly in Flux

In the analysis above, we present a variety of participation structures that students employ for engaging with their human and computational peers. Camille interacted with her computer and rarely interacted with other students, and her participation with the computer shifted throughout the episode. At the beginning of the class, she reported data from the computer, whereas by the end of class, she engaged in conversation with the computer and narrated joint activities using collective

language like "let's." In contrast, Marla and Garrincha interacted with both human and computational peers. Marla attempted to balance and manage participation in her computational and social worlds, creating space for interaction with her computer while sustaining social connections with her friends. She also leveraged social resources to support problem-solving with her model, recruiting Amy to help her balance her environment. Garrincha's stance toward interaction with Bruno looked less like "balancing" or "managing." Instead, Garrincha and Bruno built on each other's interests to support a shared, emergent inquiry. Yet, these social roles are not fixed—Camille, Marla, and Garrincha do not represent three different "types" of students. Often, research considers students in categories such as high- or low-achieving, independent or social, or other ostensibly stable, often binary, categories within the curriculum or activity. In contrast, across the unit and even within a single class session, these three students engaged in a variety of patterns of interaction with peers and with their models. This flexible stance mirrors scientists' shifting ontological stances toward non-human entities (Latour 1993).

Although Camille worked alone in the example presented above, at other times in the unit, social interaction played a significant role in her work. For example, on day 19, Camille recruited multiple students to help her try to duplicate a block in her code. After asking the three other students at her table, she asked Natalia, who was working at another table, for help. On other days, Camille worked to manage social connections and academic goals, similar to Marla's example in the analysis section. On day 20, Camille made several errors with her code because she was trying to simultaneously engage in coding and social interaction. She said, "Oh wait. This isn't the one. Ah man! I done goofed!" Between jokes with her friends, she expressed frustration with her management of her social and computational worlds, saying, "I need to pay attention!" Even so, during the end of semester interviews, Camille said that she would prefer to work on computational models with other students rather than alone. She explained, "you get more help and so you can be more advanced and you can help other people so they can be at the same level . . . because when you're by yourself, and no one's there, you kind of get stuck. And you can't get past the stuff you're going through." Thus, Camille's way of operating in the social space of the classroom was not rigidly or uniformly either individualistic or gregarious. She is a complex actor whose stance toward the other human and computational participants in the classroom shifted throughout the unit in response to particular needs and situations.

Garrincha also noticeably shifted his footing across the unit. On the first day that students interacted with computational models, Garrincha only spoke to Ashlyn, and only when she checked in with him to ask how he was doing. As seen in the example above, Garrincha's stance toward social

interaction seemed to dramatically shift when he was sitting next to Bruno. We were surprised therefore to learn in Garrincha's interview that he would prefer to "be alone because – if I be alone I could like concentrate more on what I'm doing. And if there's other people and they're talking around me – like I get distracted easily." Garrincha reinforced this sentiment on the last day of class. While the students were working on their biodomes, Garrincha asked if he could use his computer to finish working on his model. Ashlyn told Garrincha that he could ask Bruno to work on the model with him if he wanted, but he said he would rather work by himself.

Marla also demonstrates flux in footing and participation. Our analysis above demonstrates predominantly how she balances and manages the social milieu so that she can participate with her model and friends simultaneously. However, later in the project, the social dynamics and hierarchy of sixth graders took precedence, and she focused her efforts on balancing and managing those social networks rather than the populations of the agents within her computational model. In summary, in our analysis, we present examples of three students interacting with human and computational peers in different ways. Yet, our data also suggest that students do not conform to distinct types or categories. Instead, we find that social dynamics and interactive footing are constantly in flux as students engage with their computational models and their peers in the classroom, just as scientists flexibly shift their ontological stance toward non-human entities (Latour 1993).

Implications for Researchers and Educators

In this study, we focus on students' interactions with their models and their peers. However, we recognize that other contextual features, including the role of the teacher, shape classroom interactions and students' opportunities for disciplinary engagement and computational thinking. Our data suggest that computational modeling poses unique challenges in classrooms. At what might seem a classroom management level, there is what Jim Kaput described as "the millipede problem" (Kaput, Personal Communication). As a pioneer in supporting computational modeling activities in the SimCalc projects, Kaput compared the "show-stopping" moments when learners in a classroom get "stuck" to the failure of a few of a millipede's legs—the entire organism would come to a halt. Such moments often seem trivial. Camille got stuck duplicating a block, which is like copying and pasting code. Yet this prevented her and others at her table from moving forward with their models. Similarly, Garrincha and other students had trouble remembering to compile their new blocks by pressing *Run Code* before they clicked *Setup*. Students often encounter similar problems at different times, so if their teacher attempts whole group intervention (as Ms. S did for *Run Code*), some students (like Garrincha, in this example) are likely to tune out her instructions. Attempting to

help each student individually therefore seems unmanageable, and trying to do so could cause the teacher to miss opportunities to focus on the disciplinary objectives that the learning activity is intended to support. Thus, activities like computational modeling amplify the importance of effective and practical management of computers as participants in the classroom and depend on interactions between students to address otherwise show-stopping problems. A limitation of this study is that we did not address the role of the teacher in facilitating these interactions; this is an important focus for future research.

Beyond promoting whole class engagement in computational modeling, there is the challenge of promoting disciplinary engagement. Here, our data suggest that there may be no single "correct" way to scaffold for disciplinary engagement in terms of computational participation. We found that productive participation looks different over time and from student to student because productive social dynamics are constantly in flux. Therefore, rigid participation structures are unlikely to yield productive participation in computational modeling; moreover, since our data suggest that a significant feature of computational thinking with scientific models involves adopting an *array* of stances toward computational partners, rigidity itself may be counterproductive. Instead, our data suggest flexible and fluid supports for productive engagement, including opportunities for (1) personal engagement, (2) flexible participation structures, and (3) experimentation with patterns of productive engagement. Because we did not explicitly design to create these conditions, we present these suggestions as conjectures pointing to a broader design space that should be explored in future research.

First, we observed that projecting their interests and identities into their models promoted a "fusion" for Garrincha and Bruno between symbols and referents that facilitated thinking across agent and aggregate levels (Nemirovsky et al. 1998; Wilensky and Reisman 2006; Wilensky and Resnick 1999). Thus, personalizing their model supported engagement in the task as well as disciplinary thinking in terms of science content. These data align with earlier research suggesting that providing students with opportunities for ownership, agency, and personal engagement with their models can facilitate productive disciplinary engagement.

Second, our data suggest that flexible participation structures allow students to recruit support as needed. Moreover, working with other students facilitates computational participation and learning because students can share ideas and maintain social connections with their peers (Kafai and Burke 2013). Yet, flexibility can pose challenges as well; our focal students expressed difficulty balancing the sometimes conflicting demands of the social and academic worlds in the classroom. For example, Garrincha expressed a preference for working alone because other students could be

distracting. Marla and Camille preferred to work near others, but were sometimes frustrated with their own incapacity to manage their social and computational worlds (e.g., “I need to pay attention!” from Camille). These data emphasize the need for research that explores the teacher’s role in recognizing and leveraging productive dynamics that emerge while moderating, redirecting, or re-assigning dynamics or groupings that are proving counter-productive.

Third, we found that students can productively leverage sophisticated epistemic resources and approaches for making sense of their models. For example, Marla systematically explored relationships in her model by explicitly stating and revising conjectures with each run of the model. This approach is consistent with research in science education on an overt “predict, observe, explain” script (e.g., Kearney 2004). Though Marla’s strategy may not support learning for all students or in all contexts, sharing strategies with students and providing them with opportunities to “try on” these patterns of interaction could help students identify productive ways to engage with their models. Designing scaffolds is difficult, because providing strategies for engaging with computational environments can support control-oriented learners but discourage autonomous learners (Rienties et al. 2012). Furthermore, over-scripting has been demonstrated to diminish engagement and authenticity in computer-supported collaborative learning (e.g., Dillenbourg et al. 2009). Further research is needed to “balance the environment” at this higher design level—providing guidance and support with scaffolds designed to help students in these complex tasks.

Flexibility and fluidity are central to all of these suggestions. Thus, in the context of computational modeling, it seems increasingly important for research to explore and understand productive roles for teachers. Ultimately, a social environment in which models can be taken by students as meaningful participants in their investigations is productive for supporting disciplinary engagement and computational thinking, and such an environment is likely to prepare students for future work at the human-technology frontier. In this paper, we have identified three productive stances toward computational models grounded in students’ existing social resources, demonstrating that students can partner with computational models as (1) conversational peers, (2) co-constructors of lines of inquiry, and (3) projections of students’ agency and identity. Still, further research is needed to explore approaches that help teachers and students negotiate and manage interactions with human and computational participants. Such research would be valuable not only in terms of supporting computational participation but also in terms of understanding and scaffolding students’ engagement in the core disciplinarily practice of modeling in STEM.

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Compliance with Ethical Standards

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional review board VU FWA#00024139 and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. All applicable international, national, and/or institutional guidelines for the care and use of animals were followed.

Conflict of Interest The authors declare that they have no conflict of interest.

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