Modeling and Meta-Modeling in Elementary Science Learning: Physical, Diagrammatic, and Computational Models

Corey Brady, Vanderbilt University, corey.brady@vanderbilt.edu
Alison Haas, New York University, ams728@nyu.edu
Okhee Lee, New York University, olee@nyu.edu

Abstract: Our science education system is responding to three simultaneous calls for fundamental change—to promote rigorous science learning, to leverage the power of computational thinking and modeling, and to broaden participation in STEM learning to serve all students, including English learners. This paper presents preliminary data from a project to create and test the feasibility of a year-long curriculum for 5th grade science that responds to all three of these calls. We analyze student artifacts from the first (9-week) unit of this curriculum, exploring ways that students engage with three particularly challenging ideas: (a) using models to make sense of complex phenomena; (b) integrating findings from work with models across multiple (physical, diagrammatic, and computational) modes; and (c) articulating the strengths and limitations of computational modeling soon after it was introduced in the curriculum.

Introduction

Three emerging forces promise to shape the landscape of STEM education. First, a new wave of science education reform has been taking root based on *A Framework for K-12 Science Education* (National Research Council [NRC], 2012; shortened to the *Framework* hereafter) and the Next Generation Science Standards. Second, computational thinking is becoming increasingly essential for all students to become STEM professionals or participants in an information society. Third, broadening participation in STEM education is becoming ever more critical as traditionally underrepresented groups in terms of socioeconomic status and race/ethnicity are now the majority across the nation (National Center for Education Statistics, 2019). English learners (ELs) make up the fastest growing subset of the student population. According to the most recent statistics, ELs constituted 9.6% of the public-school population, or an estimated 4.9 million students (NCES, 2019). Currently, the education system is not prepared to respond to these emerging forces as they converge. From a science education perspective, efforts to develop NGSS-aligned curriculum materials are limited and successful approaches to address student diversity, including ELs, are only beginning to emerge (Lee et al, 2019). From a computational thinking perspective, efforts to integrate computational thinking in science and other STEM subjects are limited (Grover & Pea, 2013; Weintrop et al., 2016) and there are also very few efforts to promote computational thinking with ELs. NGSS-aligned curriculum materials that integrate computational thinking with ELs are virtually non-existent.

Across the NGSS and computational thinking, modeling is essential for students to engage in science and computer science, as it is essential for scientists and computer scientists to construct models of phenomena or problems (NRC, 2012; Weintrop et al., 2016). Furthermore, the ability to translate and coordinate information from multiple types of models (e.g., physical, diagrammatic, and computational) is central to both the NGSS and computational thinking. The affordances of multiple modalities of modeling are particularly important with ELs who benefit from multiple meaning-making resources, including non-linguistic modalities (e.g., gestures, diagrams, symbols, tables) as well as linguistic (oral and written) modalities (Grapin et al, 2019).

Research questions

In the science classroom, students develop and use models to explore scientific phenomena, to represent their ideas, to argue from evidence, to look for relationships between components in systems, and to identify and articulate causal mechanisms. They also learn to use different types of models for different purposes within a single investigation. In doing so, students come to understand affordances and limitations of different types and modes of modeling, building a foundation of meta-modeling knowledge (Schwarz, 2002). We argue that experience with these aspects of modeling is both feasible and valuable at the elementary level.

This study took place in the context of design-based research to develop and test NGSS-aligned curriculum that integrates computational thinking in fifth grade for all students, including ELs. Over the course a science unit that lasted approximately nine weeks (one marking period), we examined the following questions:

1. How did students develop and use models to make sense of complex phenomena in the world?
2. How did students integrate findings and features from multiple model types, to form coherent explanations of target phenomena?

3. How did students articulate the value and limitations of computational modeling?

Literature review

Researchers have begun to explore the intersections between scientific modeling and computational modeling in educational settings (Weintrop et al., 2016; Wilensky, Brady, & Horn, 2014). Below, we discuss the literature associated with each research question.

In RQ1, we ask how students model to make sense of complex phenomena. Engaging in computational modeling can allow students to build deeper understandings of causal mechanisms underlying phenomena in complex systems (Papert, 1980; Wilensky & Reisman, 2006). But, computational modeling can be challenging for both conceptual and syntactic reasons. On the conceptual side, *agent-based modeling* can make computational modeling of complex systems accessible to young learners (Klopfer, 2003; Klopfer, Yoon, & Rivas, 2004; Resnick, 1994; Wilensky, 1999) 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). On the syntactic side, visual, *blocks-based programing* environments, where programming is conducted using "blocks" (e.g., Scratch) rather than text-based commands, can lower the threshold to engaging in computational modeling. Computational learning environments that combine agent-based modeling and blocks-based programming address both conceptual and syntactic barriers. Such environments support students in appropriating knowledge by allowing them to leverage their intuitive understanding as resources in constructing and interpreting agent interactions and aggregate outcomes (Brady et al, 2015; Sengupta & Farris, 2012). These affordances scaffold students' understanding of causal mechanisms underlying phenomena in complex systems.

In RQ2, we ask how students integrate findings and features from multiple model types. Students need to "represent and explain phenomena with multiple types of models" and "move flexibly between model types when different ones are most useful for different purposes" (NRC, 2012, p. 58). For example, physical models enable students to collect and interpret data while phenomena occur, and diagrammatic models fulfill a descriptive and explanatory function (Lehrer & Schauble, 2015). Computational models fulfill additional functions, for example, to represent and investigate "aspects of a system, particularly those not readily visible to the naked eye" (NRC, 2012, p. 58); to speed up or slow down time; test and revise ideas about relationships; and run experiments that are dangerous, unethical, or impractical (e.g., studying the spread of forest fires). Through using multiple types of models, students develop the ability to use different types of models for different purposes. The ability to translate and coordinate information from multiple types of models (e.g., physical, diagrammatic, and computational) is central to both science learning (Berland et al., 2015; NRC, 2012; Schwarz et al., 2012) and computational thinking (Weintrop et al., 2016).

In RQ3, we ask how students articulate the value and limitations of computational modeling. Students need to develop an understanding of "the limitations and precision of a model as the representation of a system, process, or design" and "ways in which the model might be improved to better fit available evidence or better reflect a design's specifications" (NRC, 2012, p. 58). Moreover, students should develop an understanding of affordances and limitations across different model types. Beyond physical and diagrammatic models, the addition of computational models expands the power and authenticity of modeling. As computational models enter the learners' mental landscapes alongside physical and diagrammatic models, the affordances and limitations of all three model types come into greater relief. In the literature on representations broadly, Ainsworth et al. (in press) describe that there is relatively little research on "the process of learning a multi-representational system," compared to more research on "learning with a multi-representational system." They emphasize that students need "more explicit teaching in representational practices if we are to describe successful multi-representational learning." Moreover, they highlight that, "compared to the sizable amount of research on learning with representations, there has been relatively little to say about how teachers teach with and about multiple representations." Danish (2014) notes that research on particular agent-based modeling activities is common, while following students across modes is more rare. As the emphasis on scientific modeling (NRC, 2012) and especially computational modeling (Weintrop et al., 2016) is recent, there is limited research on students' scientific modeling (Lehrer & Schauble, 2015; Pierson, Clark, & Sherard, 2017; Schwarz et al., 2012; Weintrop et al., 2016), and virtually no research on meta-modeling (though see Farris, Dikes, & Sengupta, 2019).

Across the design work of our project, we are supporting and studying the integration of science, language, and computational thinking for diverse classrooms including ELs. Though this paper does not call out distinctive features of ELs' and non-ELs' experiences in these classrooms, other studies from our project do so (Lee et al, in preparation; Lee et al, 2019; Pierson, Clark, & Brady, in review).

NGSS-aligned curriculum integrating computational thinking

We are engaged in iterative cycles of designing, implementing, testing, and studying a yearlong fifth-grade NGSS-aligned curriculum that integrates computational thinking with all students, including ELs. This curriculum development is based on the synergy of two ongoing projects by expanding a NGSS-aligned curriculum to integrate computational thinking. The teachers participating in the project serve in a teacher advisory capacity, working closely with us to provide feedback through cycles in which we iteratively refine the curriculum.

Yearlong fifth-grade curriculum

Our curriculum uses three design principles to promote NGSS instructional shifts. The first involves supporting students to explain phenomena in the natural world (science) and design solutions to problems in the designed world (engineering), as "the goal of science is to develop a set of coherent and mutually consistent theoretical descriptions of the world that can provide explanations over a wide range of phenomena" (NRC, 2012, p. 48). The second design principle involves engaging students in three-dimensional learning by integrating SEPs, CCCs, and DCIs to make sense of phenomena or problems. The third principle involves supporting students to build coherent understandings through learning progressions over the course of instruction.

The computational thinking portions of the NGSS-aligned curriculum combine agent-based modeling in StarLogo Nova, a blocks-based programming environment with a "low threshold" of difficulty for getting started and a "high ceiling" for modeling complex systems phenomena. Our integration of computational modeling is in turn guided by three focused design principles. The first involves using agent-based modeling to support students in multi-modal reasoning about the behaviors of individual agents, which they can then use to analyze aggregate-level system behavior and develop explanations of phenomena (Sengupta & Wilensky, 2011). The second involves using a blocks-based programming environment to scaffold students' ability to articulate precise causal reasoning with diverse semiotic resources. The third design principle involves progressive accessibility to computational ideas and representations, as students advance through a use-modify-create activity progression.

Based on the NGSS and computational thinking design principles, we have developed four units that integrate computational thinking and modeling in creating scientific explanations and engineering designs. In the first unit on physical science, "What happens to our garbage?", students use computational models to construct explanations of how microbes could cause decomposition of food materials in garbage, while conserving the weight in a closed system. In the second unit on life science, "Why did the tiger salamanders disappear?", students explain potential causes for the disappearance of this endangered species in their community. In the third unit on Earth science, "Why does it matter if I drink tap or bottled water?", students design solutions to the problem of plastic pollution harming ocean animals. In the final unit on space science, "Why do falling stars fall?", students explain why they see specific meteor showers at night and at certain times of the year. Across all 4 units, students use computational thinking and modeling to engage with phenomena and problems in systems at different scales.

Unit one: The garbage unit

In this paper, we highlight students' work within the first unit on garbage. Through rigorous external reviews by expert panels, Achieve awarded the Garbage Unit the NGSS Design Badge, the highest rating for NGSS-aligned curriculum units. The anchoring phenomenon of the unit is that the school, home, and neighborhood make large amounts of garbage every day. We frame a driving question for the unit broadly: "What happens to our garbage?" In addressing this question over the course of the unit, students investigate a range of aspects of garbage decomposition (e.g., What is that smell? What causes changes in the properties of materials in garbage?) that address target NGSS performance expectations. Over the the unit, students develop coherent understandings of the nature and properties of matter to make sense of the anchoring phenomenon and to answer the driving question.

Early in the unit, students construct physical models of a landfill (called "landfill bottles") by placing food materials (e.g., banana and orange slices) and non-food materials (e.g., aluminum foil and plastic spoon) in open and closed systems. As students collect data through observations and measurements about properties of garbage materials and weights of the open- and closed-system physical models, they develop diagrammatic models to explain the processes in the open and closed systems. They observe that in the closed system, the weight does not change, while the weight of the open system decreases. Additionally, students figure out, from an investigation using agar plates and by obtaining information from an article, that *microbes* decompose the fruit from solid particles to gas particles (smell). Understanding this phenomenon involves explaining the causal mechanisms for decomposition of fruit, smell as a new substance, and conservation of weight in the closed system (RQ1). Finally, they develop computational models in an effort to explain the invisible process of how microbes cause decomposition, what smell is (as a substance), and why weight is conserved in the closed system (RQ2).

Methods

The data for this study came from a classroom of twenty students, selected for reasons of data completeness out of the larger project (involving four classrooms and two teachers). These students were in a school located in a northeastern US state. In the school district, 73% of students were classified as Hispanic, 17% Black, 8% White, 2% Asian, and 78% eligible for free or reduced-priced lunch. Of the twenty students, over 75% were eligible for free or reduced-priced lunch and a majority were Hispanic.

The study used data from two sources of artifacts produced by fifth-grade students: (a) physical, diagrammatic, and computational models in small groups and pairs and (b) science and engineering notebooks individually. Over the course of the nine-week, four-lesson garbage unit, data collection proceeded as follows:

1) Lesson 2.1, data on initial models and predictions in writing (data collection point #1)
2) Lesson 3.3, data on diagrammatic revised models and argumentation in writing (data collection point #2)
3) Lesson 4.3, data at three points:
   a) Computational models and storyboarding (data collection point #3)
   b) Diagrammatic final models and explanations in writing (data collection point #4)
   c) Meta-modeling (data collection point #5)
4) Throughout the unit, data through science and engineering journals and handouts to trace students' thinking from one data collection point to the next, especially from Lessons 3.3, 4.2, and 4.3

To analyze these data, we began with independent review of two form of artifacts from the class: (a) students' models (physical, diagrammatic, and computational) created in small groups, and (b) their science and engineering notebooks (SENs). In this first pass we individually developed emergent codes (Strauss & Corbin, 2006) that expressed patterns in thinking across students and/or resonances with our design intentions about the role of computational modeling in the garbage unit (as expressed in the research questions). We then discussed these codes to refine and combine them into a shared code book, which we used in a second pass through the data. Next, we organized coded elements of the data across students according to our research questions for this paper. Because the second year of implementation, classroom observation, and data collection for this unit was occurring during our analysis of these data, we used the ongoing experience as a means to triangulate our interpretations. Thus, while the preliminary analyses here do not support claims such as that a majority of the students in the class exhibited one or another of the patterns of thinking described below, we were guided in selecting themes for discussion by our sense from classroom observation that these patterns were recurring in the second year.

Results

In the sections that follow, we describe how students in one classroom provided evidence of their engaging with the constructs central to each of our three research questions. All quotations from student work maintain students' original spelling.

Students model to make sense of complex phenomena

An important design goal of the project is that the students engage in authentic modeling, and one indicator of authenticity is that the learning environment enables students to express ideas and propose mechanisms that either are non-normative or fail to fully explain the scientific phenomena. While we may hope that these ideas evolve when placed in conversation with those of other students, it is important that models other than the "correct" model appear in students' work and in classroom discourse. These student concepts and responses are valuable in themselves (in that they provoke the classroom community to respond to a variety of potentially conflicting ideas and conjectures); and they are also a sign of freedom and expressivity in the learning environment.

After their initial introduction to agent-based modeling, where students created programs that moved agents on the screen, they formulated conjectures that they thought could expressed and tested with computational models. From among the range of students' ideas, we select three themes: (1) ideas about the kinds of action and agency microbes might have in the decomposition process (linking to the microbe article); (2) ideas about how bacteria spread (linking to the agar experiment); and (3) ideas about why the weight of the closed landfill bottle remained the same over time in spite of decomposition inside (linking to measurements of the physical models).

The actions and agency of microbes

The Garbage Unit fosters students' scientific curiosity about the micro-processes of decomposition as well as the aggregate, emergent effects. So it is not surprising that when given a computational environment with individually moving agents, students would be interested to represent microbes. In the data, different conceptions of microbe activity emerged, each expressing foundations of a plausible account. (Each of these accounts is partially correct.)

One approach to representing microbes focused on the notion that they are living beings, attending to the idea that they might *reproduce* (microbes-as-living-beings). Another approach focused on microbes' functional role in causing food to rot, attending to the idea that they *convert* material from one form to another (microbes-as-food-transformers). These two conceptions are not actually in conflict, but they came to the foreground for different students and, for students that expressed both, they became salient at different times.

For instance, in Lucas's computational modeling storyboard, he expressed his intentions to represent microbes' vitality, writing the ideas, "Microbes touch the banana microbes multiply" and "Microbes multiply and eat the rest of the fruit." These ideas highlight microbes-as-living-beings. His third idea: "Microbes eat banana it becomes banana gas" appears to conflate concepts. On one hand, it may suggest microbes-as-food-transformers or hint at the *need* for that idea; on the other, it remains attentive to the microbes-as-living-beings concept. Here, the central perspective on microbes as eating and reproducing gives way partially to an idea needed to explain the data from the Open Landfill Bottle: namely, the strong odor and the loss of mass observed in that bottle.

With a similar blending of ideas, Takayla wrote in her storyboard (Fig 1), "The microbes will eat the banana and the banana delete" and "The microbes eat the banana and when the microbes eat the banana the microbes multiply and the banana turns into a gas." Takayla also wrote that "banana and microbes will be agents," suggesting the banana may be both acted upon by the microbes and act independently as well. Finally, Miracle expressed a possibility more in line with microbes-as-food-transformers, writing in her storyboard, "Maybe when they eat a solid banana the microbes can release gas." This idea suggests that Miracle was "thinking like a microbe" and resolving any tensions between microbes-as-living-beings and microbes-as-food-transformers by engaging in what Wilensky & Reisman (2006) call "embodied modeling."

In the course of developing their computational models, many of the students in fact shifted to emphasize microbes-as-food-transformers, as the conservation or loss of mass (weight) became a focus of the investigation. Nevertheless, some students continued committed to the idea of microbes-as-living-beings throughout the unit.

Spreading bacteria and microbes

In spite of being too small to see individually, *colonies* of bacteria were visible to students in their agar plates. A signature strength of agent-based modeling is that it supports inferences from individual activity to aggregate behavior, and some students seemed to attune quickly to this form of reasoning. For example, after working with multiple agents in the introductory computational model, Edith thought that a computational model might be used to understand *spreading* behavior. Each of her three prospective "benefits of computational models" returned to the idea of understanding aggregate spread:

Benefits of computational models

1. Computational models are useful for us to see how bacteria spreads.
2. Computational models allow us to do things we can't do in real life. Also they let us see how certain things (bacteria) spreads
3. They could show us how bacteria and microbes spread.

Edith's sense of the value of a computational model thus implicitly included the idea of bridging the agent-to-aggregate divide. While the spreading behavior per se was not an essential feature for the questions of the Garbage Unit, the introductory model gave students experience with a collection of many agents, which suggested how simple rules run by individuals might give rise to aggregate behaviors (such as clumping and spreading).

Why the closed bottle's weight does not change

Finally, one of the core data-driven investigations in the Garbage Unit revolves around the conservation of mass in a closed system. Students explained this outcome (that the weight of the Closed Landfill Bottle stays the same), in different ways, emphasizing different aspects of the system of agent activity involved in decomposition. For instance, Nelly wrote: "…the closed systems wheight didn't chang because the particules stayed in the system so they couldn't leave it so the water air gas food and smell particales stayed in the system…." Nelly is attentive to the fact that there is no escape from the closed bottle, arguing that no change in weight is actually possible.

For other students, different system features seemed important to highlight. For example, Nacio wrote: "…the landfill system was NOT changing any weight because the microbes are stealing the weight from the foods but when the microbes where feeding off the bacteria & the food it turened into gas/smell particles." This explanation focuses on the interactions between elements *within* the closed system, as opposed to the integrity and self-enclosure of that system (though Nacio addresses this factor elsewhere). In this transactional view of decomposition, weight is fixed because while processes change matter from one form to another (as the microbes "steal" weight from the food), the total weight remains unchanged.

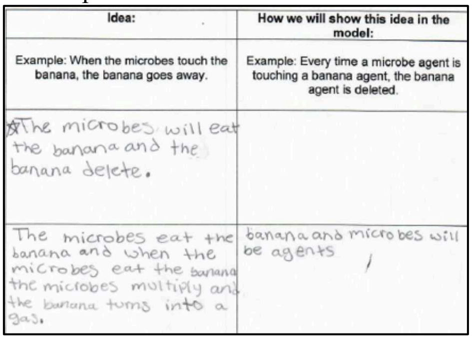
Each of these ideas highlights a feature of computational agent-based modeling: (1) the notion that the interactions among agents are causal elements in a system (e.g., microbes have a key role in decomposition); (2) the collective behavior of groups of agents (e.g., bacteria spread); and (3) the relations between activities of micro-agents and macro-level properties of the system (e.g., the macro-level conservation of weight can be explained by conservation at the micro-level).

Students integrate findings and features from multiple model types

In the course of the Garbage Unit, students created physical, diagrammatic, and computational models. Thus, as the unit progressed, students gained additional experience that could influence their thinking and serve as additional resources for explanation. It is conceivable that they could compartmentalize these models, seeing them as independent of one another, each with a focused purpose to explain a distinct part of the world or aspect of garbage decomposition. In contrast, students in our study seemed to integrate insights and ideas from different model types in explanations.

Some students explicitly drew upon different models for different forms of information in creating an integrated view of garbage. For instance, Keagan integrated key findings from across several experiments and models to gain perspective on the microbes' activity. First, he noted that the "microbes article said the microbes ate food." However, he appeared to recognize this begged the question of whether microbes were actually present. The agar experiment provided Keagan evidence of this: it "showed what was in our landfill bottles which was microbes when we swabbed." Finally, the computational model provided an explanation of *how* the microbes functioned in decomposition, namely "the microbes ate the banana [solid?] the banana [turned into?] a gas."

A second pattern in learners' integration of ideas from multiple modeling modes involved a fusion in language across modes. For instance, in preparation for modifying a "starter" model, students created a "storyboard" of interactions they were interested in investigating. The form given to students separated ideas from their computational representation (see Fig 1, below). Takayla responded to this prompt in a way that illustrated strong links between the computational representation and ideas that could be represented computationally:



Idea:	How we will show this idea in the model:
Example: When the microbes touch the banana, the banana goes away.	Example: Every time a microbe agent is touching a banana agent, the banana agent is deleted.
The microbes will eat the banana and the banana delete.	
The microbes eat the banana and when the microbes eat the banana the microbes multiply and the banana turns into a gas.	banana and microbes will be agents

Figure 1. Takayla's computational model storyboard.

Breaking down the division between ideas and their computational expression structured by the form and illustrated in the example entry, Takayla blended observations from the physical model and computational behaviors she had observed in early StarLogo Nova activities. In her second idea-row, she wrote, "…the microbes eat the banana the microbes multiply and the banana turns into a gas." As mentioned above, this statement began the work of combining a *living* theory about the microbes (that they eat food matter and multiply, microbes-as-living-beings), with a *transformational* theory about microbes' effect on food matter ("the banana turns into a gas," microbes-as-food-transformers). Here, because "banana and microbes will be agents" Takayla was struggling to interpret the world through dual agency fostered by the agent-based modeling environment in which *any* agent can be programmed to initiate actions. Similarly, when she wrote, "The microbes will eat the banana and the banana delete," she seemed to be combining a theory of microbes (they eat) with a reference to a concrete code block she had interacted with (the "delete" block causes an agent that executes the block to disappear).

Finally, in a third form of blending ideas across modeling modes while building an explanation of the conservation of weight in the closed landfill, Nacio said, "I think the weight of the closed system stayed the same because the air, smell, gas, and water particles couldn't get in or out, and there were no fruit flies to get in." Here, he integrated experiences of and data from the physical models (weight of closed system, fruit flies as potential actors) with some of the conceptions that drove the diagrammatic and computational models (particles as a basis for all matter, including "air, smell, gas, and water"). Nacio argued that the barrier of the closed system would not allow particles (or fruit flies) *either* to exit or to enter.

Students articulate the value and limitations of computational modeling

Our third research question concerns students' evaluation of the strengths and limitations of computational models and modeling. Many students commented on the positive contribution of computational models to their garbage investigation. They related a video about computational models (simulating a fire escape plan for a building) to their investigations, and they reflected on the insights they gained from their own computational modeling work. The first discussion of computational modeling in the unit foregrounded that computational models allowed scientists to run experiments to understand processes (such as evacuation and flight patterns in case of fire) that could not be run in the real world, for ethical or safety reasons. Some students connected these ideas with their work in the unit. For instance, Lucas argued that computational models "are useful because they help us see how something would work. They allow us to stay safe." Lucas went on to say that they "help us by trying it in code to see if it is [dangerous]." Takayla elaborated a perspective similar to the one Lucas offered about computational models and experiments that could not be run in the real world. She said:

> The computational models shows us how thing go for example: on the computer we are using it to see what will a fire do and people are running away from it. But you can't do that in real life because a lot of people can get hurt and its only for our safety.

That students connect this image of computational modeling with the work in the Garbage Unit suggests a view of the microscopic universe as an eventful and active environment. Computational models offered a means to gain insight into that world, its actors (including microbes), and the mechanisms behind its phenomena. In the case of garbage, Takayla said they "help us figure out what is causing the food in the landfill bottles to decompose." Interestingly, the computational models didd not simply show the world "as it is," for Takayla, but rather "helps us figure out" the cause of decomposition. Later in Takayla's notes, causality extends to the modeler herself, as "it" (the computational model) "[is] causing us to see what is happening inside the landfill bottles."

Other students brought up features of computational models related to their affordances for representing dynamic processes. In explaining the value of computational models from her perspective, Blanca argued that computational models address a problem of scale, saying "they let us see things we can't see," that is, "things that is smaller than a rock." Thus far, computational models appeared to offer her a kind of virtual microscope. But Blanca went on to say that computational models show "how the landfill start decomposing and what they will look like after a couple of days." Here she seemed to highlight the notion that computational models enable a dynamic view of processes as they unfold over time.

Finally, some students described benefits of computational modeling that suggested it made phenomena more approachable. For instance, Nelly made reference to StarLogo Nova's visual representation of agents, saying, "[It] lets us change our animal." On one hand, this could be seen to refer to a merely "decorative" element of the modeling environment – the physical guise that the agent is given. However, Pierson, Brady, & Clark (2019) show how these features of StarLogo Nova can provide entry points for connecting with agents in simulations.

In the notes and artifacts from this first unit, we did not see students reflecting spontaneously on the limitations of computational models, but we expect that in later units they may express ideas of this kind, on their own or in response to explicit questions in the curricular materials.

Conclusion

This preliminary analysis of patterns in students' writing on worksheets and in their science and engineering notebooks suggest that many were able to use computational models to make sense of key features of the complex phenomenon of garbage decomposition. Students also were able to integrate ideas they developed over the course of the Garbage Unit in activities that involved modeling across several modes, in physical, diagrammatic, and computational models. Finally, some were able to reason explicitly about the distinctive value that computational models added to their investigation. Our analysis does not support claims that these ways of thinking were adopted by a *majority* of the class, but it does suggest that 5th grade students are capable of reasoning about complexity; that they can integrate perspectives and insights from multiple modes of modeling; and that they can appreciate key affordances of computational models. These are powerful elements of sophisticated modeling and meta-modeling practices, suggesting that the ambitious vision of science learning expressed in the NGSS can be realized for all learners, including ELs.

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