

Article

Expanding Opportunities for Systems Thinking, Conceptual Learning, and Participation through Embodied and Computational Modeling

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Abstract: Previous research has established that embodied modeling (role-playing agents in a system) can support learning about complexity. Separately, research has demonstrated that increasing the multimodal resources available to students can support sensemaking, particularly for students classified as English Learners. This study bridges these two bodies of research to consider how embodied models can strengthen an interconnected *system* of multimodal models created by a classroom. We explore how iteratively refining embodied modeling activities strengthened connections to other models, real-world phenomena, and multimodal representations. Through design-based research in a sixth grade classroom studying ecosystems, we refined embodied modeling activities initially conceived as supports for computational thinking and modeling. Across three iterative cycles, we illustrate how the conceptual and epistemic relationship between the computational and embodied model shifted, and we analyze how these shifts shaped opportunities for learning and participation by: (1) recognizing each student's perspectives as critical for making sense of the model, (2) encouraging students to question and modify the "code" for the model, and (3) leveraging multimodal resources, including graphs, gestures, and student-generated language, for meaning-making. Through these shifts, the embodied model became a full-fledged component of the classroom's model system and created more equitable opportunities for learning and participation.

Keywords: science education; scientific modeling; computational modeling; embodied modeling; multimodality; English learners

1. Introduction

Computational modeling is a powerful tool for helping K-12 students explore and learn about complex systems [1–3]. Yet due to barriers arising both from the syntax and concepts of computational representations, computational thinking and modeling can be challenging for both students and teachers. In response, researchers have worked to design programming environments and learning activities that make computational modeling more accessible. One such approach to support computational modeling is embodiment or enactment. In an embodied model, students role-play agents in a system (e.g., plants and animals in an ecosystem) to explore agent actions and interactions, as well as system-level, emergent phenomena from the perspective of these agents [4–7]. To enact agents, students typically follow rules, which are sometimes framed as the "code" or "program" for the agents in the embodied model.

In addition to these affordances of embodied modeling, we propose that embodied modeling activities could be designed to invite and leverage students' linguistic resources and multimodal

representations, in turn supporting learning and participation, particularly for students classified as English learners (ELs). Research in bilingual education and science education shows that multilingual students benefit from deploying their full range of meaning-making resources in classrooms [8], including linguistic resources (resources from named languages, like English or Spanish) as well as other semiotic resources (nonlinguistic modes, like images, gestures, actions, symbols) [9,10]. Building upon this work, we explored how embodied modeling activities could be enriched with additional representations beyond embodied actions, including students' everyday resources (e.g., graphs, gestures, student-generated language) and social interactions.

In the context of an iterative design-based research project in a sixth grade STEM (science, technology, engineering, and math) classroom studying ecosystems and population dynamics, this study explores how embodied modeling can expand opportunities for participation and for learning about complex systems. We illustrate how embodied modeling activities were refined with each cycle of our design to offer students distinct ways of understanding their computational models and the ecosystems they represented.

1.1. Computational and Embodied Modeling

Research demonstrates that computational modeling promotes engagement and learning in K-12 science classrooms. Computational modeling makes representations of systems visible, executable, and interactive, enabling students to explore the causal mechanisms that underlie complex systems [1–3]. In this way, computational modeling can help students develop conceptual understandings as well as domain-specific and mathematical reasoning skills [11–14]. In addition, computational modeling offers learners new representational infrastructures and new ways of making sense of complex systems [12,15,16].

But computational modeling can be challenging for syntactic and conceptual reasons. Learning environments that combine visual programming with agent-based models (ABM) address these barriers [17–19]. 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 [3,20–22]. ABMs are computational models of systems, which begin from modeling the micro-level actions and interactions of system components (the “agents”) and then instantiate large numbers of these agents to simulate the macro-level aggregate behaviors of the system as a whole. ABMs support learning due to representational correspondences between agents and conceptual entities (e.g., fish in an ecosystem) and intuitive correspondences between agents and learners, which invite learners imagine themselves as agents [2,3]. By identifying agents, giving them rules of behavior and interaction, and “running” the system, ABMs enable a modeler to “grow” a complex system from the interactions between simple components [23]. This enables the computational representation to simulate emergent, whole-system behaviors so that students can reason about the system across agent and aggregate levels [13]. In this study, we used an ABM environment, StarLogo Nova (SLN), to help students explore population dynamics in an ecosystem. SLN combines a block-based programming environment with an agent-based simulation engine and a 3D renderer optimized for modeling complex systems. It also includes the ability to use tables and graphs to visualize data. Existing research shows that SLN can support learning about complex systems [24,25] as well as disciplinary engagement and computational thinking [26].

Embodied modeling can also provide resources for understanding complex systems and the logic that underlies computational models [27–30]. One approach to embodied modeling involves directly integrating and blending computational and embodied modes. For example, in participatory simulations (PartSims, [7,31–34]), students role-play agents to enact phenomena. PartSims can be mediated with a variety of networked, handheld, and wearable technologies [7,31,32] or with socially-structured rules and roles [35]. Similar to computational ABMs, PartSims enable learners to take on the goals and perspectives of a specific agent to produce and experience emergent system-level phenomena. In a

related approach, participatory modeling [36,37], students use augmented reality technology to animate a model designed by researchers to help learners make sense of a scientific phenomenon. As with technology-mediated PartSims, participatory modeling fosters interconnectedness between embodied and computational modes [38], which can be a strength and a limitation. While these approaches translate students' tacit interactions into emergent effects and mechanisms [5,7], they largely offload the interpretive and representational work of making sense of an embodied performance to the computer.

Other approaches to embodied modeling maintain separation between computational and embodied modes [4,39], and therefore could afford different forms of discourse and contestation as students attempt to map actions, interactions, and outcomes from one model to another. In the current study, we analyze discourse about an embodied model that is based on, but not directly linked to, a computational model. From the first iteration of our design, embodied modeling was intended to support students' engagement in computational modeling by presenting students with embodied rules to enact, similar to the code in their computational models.

1.2. Multimodal and Everyday Resources for Learning and Participation

Based on their potential to leverage multimodal representations and everyday resources, we propose that both computational and embodied modeling could expand opportunities for learning and participation in STEM classrooms, particularly for multilingual students (including students classified as ELs). Research demonstrates that multilingual students benefit from deploying their full range of meaning-making resources in K-12 classrooms [8]. Meaning-making resources include linguistic resources (resources from named languages, like English or Spanish), as well as other semiotic resources (nonlinguistic modes, like images, gestures, actions, and symbols) [9,10]. Each of these resources can be valuable for sensemaking, because each mode has distinct affordances [40–42]. For instance, visual modes afford and demand representations of spatial relations between objects, such as proximity and adjacency, whereas representing spatial relationships is optional in written modes. As a result of these unique affordances, meaning cannot be precisely or stably translated across modes [40]. Adding complexity, the meaning of a multimodal representation is often contingent on interactions among the multiple modes within the representation [42,43].

In science classrooms specifically, encouraging multilingual students to leverage their full range of linguistic resources has been shown to promote language development, high-order thinking, and conceptual understanding [44,45], contributing to more equitable learning environments for multilingual students [45,46]. Moreover, reaching beyond linguistic resources, multimodal resources can further support STEM learning for multilingual students [47,48], because students can integrate multiple representations to engage in complex and rigorous disciplinary thinking [49,50]. Inviting and valuing students' multimodal resources legitimizes their communicative practices as valid forms of expression and inquiry rather than positioning supports for students' resources as mere scaffolds toward a higher-status "academic" English. This stance aligns with accounts of multimodality in professional disciplinary practices; although engaging in STEM practices involves using language, these practices are rarely accomplished through language alone. The multimodal nature of disciplinary practices is well-documented by studies of professional scientists and engineers [42,51–53], which explain that multiple modes and representations not only offer more channels for expressing ideas, but also offer unique perspectives on phenomena, supporting new understandings of phenomena.

In STEM education, recent research has begun to explore the affordances of computational learning environments for inviting and leveraging multilingual students' linguistic and cultural resources [54,55]. For example, Radke and colleagues [54] describe an instructional design in which students used a multilingual, multimodal programming environment to understand a personally meaningful phenomenon—the effects of Hurricane María on Puerto Rico. This design invited students' resources, cultures, and experiences by engaging them in statistical modeling practices while also exploring "human stories of migration . . . in less quantitative formulations" (p. 1371). Thus, integrating

students' multilingual and multimodal resources supported them in making sense of disciplinary concepts applied to a real-world context.

Building on this work, we propose that embodied modeling activities have the potential to further expand the range of multimodal resources available for meaning-making, by inviting students to shift their perspective of a complex system by taking on the role of agents within the system. Moreover, embodied modeling could help students create shared experiences from everyday language and interactions that could serve as resources for engaging in computational modeling and for reasoning about complex systems more broadly. In this study, we explore the potential of embodied modeling for creating more equitable opportunities for learning and participation, particularly for students classified as ELs.

1.3. Research Questions

Previous research has established that, even as isolated experiences, forms of embodied modeling can support learning about complex systems. Separately, research has demonstrated that increasing the range of multimodal resources available to students can support sensemaking in STEM. In this study, we bridge these two bodies of research to consider how embodied modeling can function as part of a multimodal *system* of models to support students learning and reasoning about complexity. In describing classrooms' developing model systems, we conceptualize models and modeling experiences in terms of a node-link representation of a network. Individual models and modeling experiences are the nodes in this network. They derive their value for learning not only from their internal structure, but also from the connections, or links, that learners form between them and other modeling experiences. We conceptualize embodied modeling as a node that is connected to other forms of representation (e.g., students' computational models). We aim to understand how shifts in embodied modeling activities can enhance their intrinsic value as modeling experiences and also strengthen their connections to other nodes within students' emerging system of models, as well as foster connections to real-world phenomena and to other diverse multimodal resources.

Initially, we intended for the embodied modeling activities in our design to support students' understanding of the computational model. However, as students engaged in embodied modeling, our understanding of the relationship between the computational model and the embodied model shifted. We began to see potential for the embodied model to be a full-fledged component of the classroom's model system that could be used for exploration and discovery about systems phenomena. In addition, we iteratively expanded the resources used in embodied modeling to include students' social interactions, representations from the computational model, and students' everyday communicative resources. In this context, to consider the potential of embodied modeling for supporting learning and participation, we ask:

1. With each design cycle, how did the conceptual and epistemic relationship between the computational model and the embodied model shift?
2. How did embodied modeling activities shape opportunities for learning and participation, particularly for students classified as ELs?

2. Materials and Methods

This paper analyzes data collected during three cycles of a design study [56] that engaged students in multiple forms of modeling (including diagrammatic, physical, computational, and embodied modeling) to support their understanding of population dynamics and the flow of energy and matter within an ecosystem. The larger study comprised seven successive implementations of a 9-week STEM unit. In the present study, we focus on three early iterations of the design in which our approach to embodied modeling emerged and stabilized. We analyze whole-class videos to understand the evolving relationship between computational and embodied modeling and to understand how embodied modeling created opportunities for students to gain new perspectives on ecosystems and to investigate ecological phenomena through modeling. We view shifts in students' participation as

reflective of their learning (about ecosystems specifically, and about systems thinking and modeling generally), although we occasionally separate discussions of learning and participation when describing the consequences of revisions to the embodied modeling activities.

2.1. Participants and Research Context

This iterative design study is part of the larger SAIL + CTM project (NSF DRL#1503330), for which it serves as a design vanguard by developing and testing principles for integrating multimodal modeling and computational modeling that could be applied in the more formalized SAIL + CTM curriculum. Data were collected in a public middle school in a small suburban district in the southeastern US in collaboration with a STEM teacher, Ms. S, and seven of her sixth grade classes. All participants gave their informed consent for inclusion before they participated in the study. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Vanderbilt University Institutional Review Board (#181016).

Ms. S, who was in her 26th year of teaching at the beginning of the project, and the first author, Ashlyn, codesigned and cotaught all lessons. In this sense, Ashlyn took on the role of a participant-observer [56,57] in the classroom, both collecting data and supporting instruction by helping Ms. S. facilitate whole class discussions and small group activities. The unit was designed to support ecology and life science standards from the state and from the Next Generation Science Standards. Lessons took place three times a week during the students' 56-min STEM class (between 21 and 24 class sessions per 9-week cycle; the length of the unit varied based on the school's schedule each quarter). The STEM class was a one-quarter (9-week) course that was separate from the school's science course for sixth grade. This afforded Ms. S. some flexibility in her curricular design, though she considered supporting science standards to be a primary goal of the STEM class. Because the STEM class was 9 weeks long, Ms. S. welcomed a new cohort of students each quarter, allowing four design iterations in the span of a school year. Because the STEM course was required, Ms. S. saw each of the school's sixth grade students in one of the quarters of the year.

We analyzed data from three of Ms. S's 9-week sixth grade classes (August 2018–March 2019, 13–15 students per quarter, 42 students total). We focus on these three classes because over the course of these iterations, our design shifted significantly in response to students' participation in embodied modeling; the design stabilized in later iterations. 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: 55% of students identify as White, 34% as Hispanic or Latino, 7% as Black or African American, 4% as Asian, and 8% are classified as ELs¹. In each of Ms. S's classes, between two and five students were classified by the school as ELs. All of these students identified as bi/multilingual and as speakers of Spanish and English, although they described their linguistic resources in different ways (e.g., some students identified as speakers of "Mexican" or "Honduran" Spanish). In addition to students classified as ELs, other students identified as bi/multilingual, including speakers of Spanish and Korean. Nevertheless, most students (and Ms. S) identified as monolingual English speakers. Our data therefore offer insights about supporting students classified as ELs within a predominantly monolingual setting that has historically privileged English over other linguistic resources.

2.2. Initial Design

The 9-week unit was framed by two design challenges: students designed a biosphere (a closed-system physical model that included plants, snails, and guppies), and they programmed a computational

¹ All students entering this district complete a Home Language Survey which is used to determine if language proficiency evaluation is needed. Students are classified as ELs based on the IPT and ELDA assessments, which are used along with content-area state assessments to monitor their progress annually. Based on these assessments, the district determines whether a student's English proficiency "does not enable them to succeed in school". According to the district website, students are typically classified as ELs for four to seven years.

model to represent a larger ecosystem of plants, snails, guppies, and guppies' competitors and predators (Figure 1). Throughout the unit, the students gathered and re-represented the guppies' environment with increasing complexity as they addressed classroom-generated questions about this environment as an ecological system. In this paper, we focus specifically on embodied modeling activities (one class session in Quarter 1, two class sessions in Quarters 2 and 3). These activities were initially designed to support students' engagement in computational modeling by helping students make sense of the code in their computational models and how it could be used to model ecosystems. Over the course of the study, the nature and status of the embodied modeling activities shifted, as did their connections and relations to the computational modeling activities.

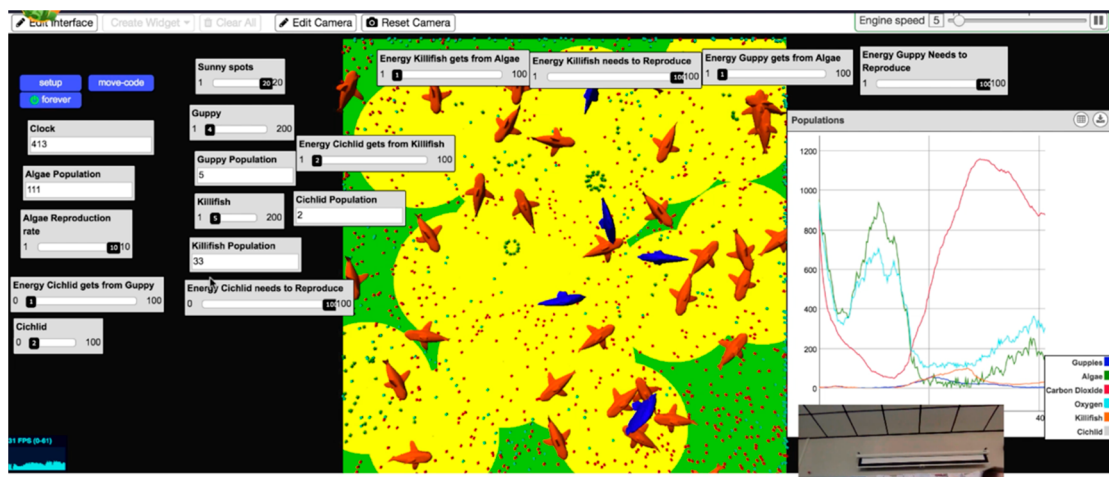


Figure 1. Computational model with algae (producer), guppies (consumer), killifish (competitor), and cichlids (predator). The graph on the right represents populations of each organism, as well as particles of oxygen and carbon dioxide available in the ecosystem.

Initially, the embodied modeling activities were intended to scaffold students' participation in computational modeling. Although some of the students had *used* SLN models before engaging in this unit, and a few of the students mentioned experience with *Scratch*, a similar agent-based visual programming environment, none of the students had programmed SLN models previously. By enacting code similar to the program in the computation model, we anticipated that students would develop a deeper understanding of the relationship between the code for the agents and their actions and interactions. Within each quarter, in the first "run" of the embodied model, students took on the role of algae or guppies; in later runs, they added roles for killifish (competitors), then cichlids (predators). This was intended to preview adding killifish and cichlids to the computational model.

Students were given programs for each role in the embodied model (algae, guppy, killifish and cichlid) and an energy log to track their energy over time (see Appendix A for embodied modeling materials). These programs were designed to represent agents' actions and interactions. Algae were programmed to die (sit down) when eaten and to re-grow (stand) over time. Guppies, killifish, and cichlids were programmed to move, lose energy when they moved, gain energy when they reached food (algae for the guppies and killifish, guppies for the cichlid), and die (sit down) when they ran out of energy. Time was marked by "ticks"; in each tick, students followed each step of their program. Ms. S or Ashlyn signaled the beginning of a new tick by ringing a bell. Ticks were not always the same length of time for the humans enacting the model—a tick ended when all students had finished executing their programs. Ms. S or Ashlyn sometimes "paused" the model to allow the students to reflect on the status of the modeled ecosystem, and they "stopped" the model either when most of the fish had died or when it seemed like the fish and algae were "balanced" (i.e., they would survive indefinitely). After stopping the model, they facilitated a discussion about what happened during the model; then, the students would switch roles and run the model again.

2.3. Data Sources and Analysis

To understand how embodied modeling activities afforded and shaped opportunities for learning and participation, in this paper we focus on whole-class videos of students participating in embodied modeling activities. Our understanding of students' participation in these activities is also informed by additional data sources collected as part of the larger study, including student work (sketches, computational models, photos of diagrammatic and physical models); screen recordings of students' activity while using computational tools and engaging in computational modeling, and 25-min semi-structured interviews [58] (see Appendix B for interview protocol) conducted by Ashlyn during the last week of instruction that focused on students' experiences and perceptions of the unit (5–6 focal students were selected per quarter with input from the sixth grade teaching team to represent a range of backgrounds, academic performance, and engagement; at least two focal students per quarter were classified by their school as ELs.) Each of these additional data sources was used to triangulate our interpretation and analysis of whole-class discourse. Further, as a form of negative case analysis, we looked for references to embodied modeling activities in these data to ensure that students' actions and interactions did not contradict the themes that emerged in our analysis of embodied modeling activities.

Because this work is part of a design study [56,59], data analysis necessarily unfolded in relation to students' participation in the designed embodied modeling activities. Our ongoing analysis was critical to informing the design and refinement of learning activities. Initially, we focused our analysis on evaluating and revising conjectures [59] describing our conceptions of how embodied modeling could be leveraged to support students' engagement in computational modeling. As we analyzed data, we recognized the affordances of the embodied model as a multimodal tool for understanding complex systems in its own right, and we shifted our focus to consider how embodied modeling shaped learning and participation in these classrooms (Table 1). In the Results section, we present episodes of embodied modeling that informed these revisions to our conjectures.

Table 1. Conjectures, their manifestation in the design, and revisions over three design cycles.

Quarter	Initial/Revised Conjecture	Manifestation in Design	Revisions to Conjecture
1	Embodied modeling helps students “read” code to understand agent actions and interactions as well as system-level effects, making computational modeling more accessible to students.	Students are given embodied code to enact that is similar to the code in their computational models of ecosystems.	Embodied modeling relies on all students' insight and input. Embodied modeling can support learning about new aspects of phenomena.
2	Embodied modeling can offer students opportunities to understand computational models and real-world phenomena by inviting students' questions and ideas.	Students are given code to enact and remix (modify) to ask and answer questions about ecosystems.	Students' resources (e.g., social interaction) can be generative resources for conceptual learning through embodied modeling.
3	Embodied modeling can offer students opportunities to enrich their understanding by inviting students' questions and ideas and by legitimizing and leveraging diverse multimodal resources.	Students are given code to enact and remix, and they are invited to used and create linked, multimodal representations to make sense of embodied modeling in relation to other models and real-world phenomena.	Embodied modeling can support more equitable learning and participation by positioning diversity as an asset in STEM.

The iteration-level changes to conjectures about modeling and learning were supported at the micro-level through reflective debriefing sessions that occurred throughout the implementation. Specifically, to revise conjectures, Ms. S and Ashlyn debriefed after each class session, discussing how the designed activities contributed to intended objectives for learning and participation, as well as highlighting unexpected interactions and potential missed opportunities for supporting learning and

participation. For example, during the first implementation of the design, we realized that we had been approaching the students' initial run of the embodied model primarily as a check for students' understanding of the embodied code, and we therefore had passed over opportunities for students to critique the model in relation to the computational model, their physical models, or the referent ecosystem. We initially conjectured that embodied modeling would help students understand the relationship between the code, agent actions and interactions, and emergent outcomes at the system level. In response to students' participation in the design, we revised our conjectures to describe how embodied modeling could more generatively shape students' understanding of other models and the referent ecosystem (e.g., using the embodied models to consider why guppies turn as they move or to make predictions about effects of predators). These insights led us to revise our conjectures and refine our curricular materials, shifting our approach to embodied modeling in subsequent design cycles. In this case, we revised the learning activities to invite students to address their own questions related to the embodied model, the computational model, and the referent ecosystem by remixing (modifying) the embodied code.

Our retrospective analysis considered themes from these design cycles in more depth. For each of the three implementation cycles, we began by creating content logs [60] of the classroom videos to index classroom interactions during embodied modeling activities. We used the content logs as a basis for identifying episodes that served as evidence for our conjectures as well as episodes that informed revisions to our conjectures. We transcribed these episodes for more nuanced turn-by-turn analyses of students' participation in and reflection on embodied modeling. In creating transcripts, we attended not only to classroom discourse, but also to multimodal resources leveraged in students' meaning-making (e.g., gestures, tools, representations [42]). With inductive and grounded methods, we examined the videos along with the transcripts to look for specific evidence of the themes identified in our ongoing analysis [61,62]. Through this process, we strengthened conjectures with evidence that demonstrated how embodied modeling supported learning and participation in these classrooms.

3. Results

Traditionally, embodied modeling involves students role-playing agents in a system using an established program to understand how agent interactions shape emergent system-level outcomes. Building from this approach, we explore how embodied modeling could offer students a way to test their own ideas using personally meaningful resources. Below, we describe three iterations of embodied modeling in our study. We illustrate how the conceptual and epistemic relationship between the computational and embodied model shifted with each cycle of the design, and we analyze how these shifts shaped opportunities for learning and participation, particularly for students classified as ELs.

In quarter one, the embodied model was initially positioned as a rehearsal and a comprehension check for the computational model, but it evolved to become a reflective medium that animated the computational model, relying on each students' unique contributions and perspectives for meaning-making. In quarter two, embodied modeling became a space for active and collective modeling in its own right, as students remixed the embodied code to test their own ideas about ecosystems. In quarter three, embodied modeling was enriched with linked, multimodal representations (e.g., graphs, gestures, student-generated language); the model produced data that provoked questions about ecological phenomena that could be addressed within the embodied model or in dialogue with other models, including the computational model. Thus, the embodied model, which was originally intended to scaffold computational modeling, became a full-fledged component of the classroom's model system. With each iteration of embodied modeling, opportunities for learning and participation expanded as students increasingly leveraged multimodal resources to explore nuanced aspects of a complex system.

3.1. Quarter One: From a Rehearsal to a Reflective Medium

Following from previous research about embodied modeling, the first iteration of our design (October 2018, quarter one) aimed to scaffold students' participation in computational modeling by helping students understand the code in their computational models. However, we observed that embodied modeling also created unique opportunities for learning and participation, because students' contributions were necessary for meaning-making within the embodied model, and because the embodied model highlighted aspects of ecosystems that were backgrounded in students' other models. In this section, we describe how, in response to students' participation in embodied modeling in quarter one, we shifted from seeing embodied modeling as a rehearsal for the computational model to recognizing the potential of embodied modeling for building shared conceptual understandings based on students' ideas and perspectives.

3.1.1. Conceptual/Epistemic Role of Embodied Modeling

We initially included embodied modeling in the designed learning activities to help students engage in computational modeling. In their computational models, students used code snippets that represented guppies eating algae (Figure 2). This code was complex: to "eat" algae, on collision with algae, the guppy deleted the algae and added to an "energy" variable. Guppies needed to eat to survive, because with each step they subtracted from their energy. When their energy was less than zero, the guppies died. Although students implemented this logic in their programs, it was not always clear that they understood why or how the logic worked.

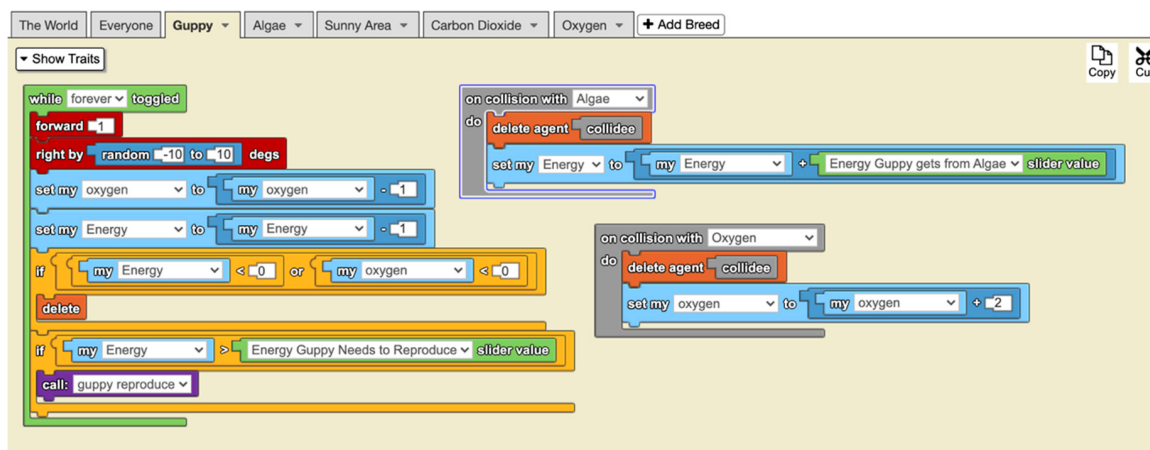


Figure 2. Computational model code for guppies.

Based on previous research, we intended to use embodied modeling to help students "read" the computational model and understand how code blocks produced specific interactions and outcomes in their computational models. Understanding this logic would support students in later adding competitors and predators to their computational models and would help them predict how these new agents might affect population dynamics in the modeled ecosystem. As students rotated through different roles in the model, they were accountable for understanding the role of each agent. Moreover, stepping through the code for each agent could help students more deeply understand how each line of the code translated to outcomes in the model [4,5,7]. Each agent's role was visible and important to the overall functioning of the model, so we anticipated that embodied modeling would also help students understand the necessity of each programmed behavior and support them in "debugging" embodied actions when they noticed implementation errors made by themselves or their peers. These debugging dynamics are consistent with "syntonic" learning (learning that is grounded in students' sense of themselves) in agent-based settings, including body and ego syntonicity [2] and social syntonicity [63].

These goals for embodied modeling were evident in how Ms. S introduced embodied modeling to the students. She initially focused on helping students read, interpret, and enact the program for each role (guppies and plants). Ms. S saw this task as procedural and attempted to move through it “quickly”. She said, “Let’s look at, really *quickly*, if you’re algae, how are you programmed? Somebody read that for me on your sheet”. After a student read the program, Ms. S, said, “Who thinks they can act it out really *quickly*?” In designing this embodied modeling activity, we did not initially create space for students to interrogate or question the program; our goal was to help students make sense of the program to inform their understanding of the computational model, scaffolding students’ use of the computational model to make sense of the referent ecosystem.

However, the distributed awareness of roles within the computational model shifted participation structures in the classroom by positioning each student as having a unique perspective on what happened in the model; students’ different roles and positions within the model offered each student a different view of what happened during each run, so each student’s voice was important for interpreting the model. As students enacted (rather than observed) the system, they noticed interactions that were backgrounded in their computational models. Noticing and questioning these interactions was generative; it created space for students to consider new aspects of the phenomenon, deepening their understanding of interactions and emergent outcomes in this complex system. As we began to attend to these unexpected opportunities for complex systems learning, our understanding of embodied modeling shifted; whereas we originally conceptualized this activity as a way to “rehearse” the computational model, we began to position the embodied model as a medium for reflecting on specific interactions and outcomes within an ecosystem. We illustrate these opportunities and their significance for learning and participation below.

3.1.2. Significance for Learning and Participation

Based on previous research about embodied modeling, we anticipated that by participating in the embodied model, students would hold themselves and their peers accountable for understanding and enacting the embodied code. We intended this form of participation to support students’ understanding of the computational model when students returned to programming. However, in this first implementation of embodied modeling activities, we also noticed that the nature of the embodied model made each student’s unique perspective of the model valuable; understanding what was going on in the model required all students to share and integrate their experiences and data. Thus, the embodied modeling activities not only made all students accountable for performing their roles adequately, but it also required their insight and input. Attending closely to the embodied program in this way created new learning opportunities for students, as they noticed interactions and ecological phenomena from new perspectives.

Because each students’ role was critical to the model as a system, it was important that the classroom built a shared understanding of the program. Nuances of the program that were previously offloaded to the computer played an important role in social negotiations around the embodied model. As a result, students who rarely asked questions during computational modeling activities asked questions about the embodied model. For example, Katherine asked about how energy changed during a “tick” when a guppy ate algae.

Ms. S: I saw someone eat some algae. So, did you check—did you put the extra two points by it, Sofia?

Katherine: So, you write down 11?

Ms. S: Wait, stop, Katherine has a question for the class.

Katherine: So, if you begin with 10 energy, and we’re on nine energy, if you eat algae is it plus two, 11 energy or 10 energy?

Ms. S: Well remember, every time you take a step, what happens?

Students: Lose one.

Ms. S: Every time you touch algae, what happens?

Students: Gain two.

Ms. S: So there you go.

Prior to Katherine's question, several small groups of students were talking with each other. When Katherine asked her question, all students turned toward Ms. S, and many helped answer (multiple students answered "Lose one" and "Gain two"). Because Katherine's question was about how the model should be enacted, it was relevant to each of the students, not only to ensure they understood how the model worked, but to ensure that Katherine was following and interpreting the program in the same way they were.

In addition, each student's unique perspective was necessary for making sense of the model's representation of the ecosystem's behavior. Each student held information about the model that would have been inaccessible in the computational modeling environment (the energy of each agent, for example, cannot be seen in the StarLogo Nova interface, whereas in the embodied model, records of energy were accessible in each student's energy log). As agents embedded within the model, each student saw a different snapshot of what was going on in the model, because knowledge was distributed across each agent. For example, at some points, it seemed like all of the algae had died, and the guppies would not have enough to eat. Because each algae plant died and would therefore re-grow at a different point in time, only the algae themselves knew when they would re-grow, once again becoming available as food for the guppies. At times, algae would share this information with guppies (David: "I'm almost re-grown") but in other cases, algae would try to stand up quietly so that guppies would not notice they had re-grown. As an observer or as a guppy, it was difficult to predict how soon the algae would re-grow, and therefore difficult to predict an algae shortage. Similarly, each guppy knew only their own energy level, so although a guppy could predict whether they were likely to reach algae before they ran out of energy, observers and other agents could not tell when a guppy was running out of energy. In response, to gauge the status of the modeled ecosystem, Ms. S would sometimes pause the model and ask students to report on the system:

Ms. S: What do you have on your sheet right now?

Students (algae): Nothing!

Reid: I have nine [energy].

Ms. S: So, you've taken one step and you've eaten nothing?

Reid: I've taken like four steps and I ate Christian.

Ms. S: Okay who else can share theirs?

Grace: I have 13.

Ms. S: Okay tell us how that happened.

Grace: I ate all of them [algae], and I subtracted it.

Ms. S: What about your steps, did you subtract them? Nicely done. Jasmin what about you?

Jasmin: I took steps and I ate Anthony.

Ms. S: Very good!

Ashlyn: Have we seen anybody die yet?

David: I'm dead.

Ashlyn: So, let's keep going.

As illustrated above, it was difficult for an observer (like Ms. S or Ashlyn) to gauge the state of the ecosystem without checking in with individual agents. This positioned each student's experience and status as important in the model, whether they were representing algae or guppies, and whether they were dead or alive. Throughout the class period, students increasingly shared status updates without prompting. For example, during the last run of the model, Anthony said "I'm the lone algae", as the model was running, reporting on the rapid decrease in algae in the ecosystem and drawing the attention of the fish (Sofia: "I'm going to eat you!"). After running the model, Madison (a predator) and Ross (a competitor) explained how they made the environment more difficult for the guppies (Madison: "I would eat them all", Ross: "I ate all the algae, and it was delicious").

Attending closely to actions and interactions in this way highlighted for students aspects of ecological phenomena that were backgrounded in their previous models, creating new opportunities for conceptual learning. In the computational models, students had programmed guppies to move by taking one step forward and turning (Figure 2). Students programmed the guppies to turn (rather than stepping without turning), because it made it look like guppies "wiggled" while they swam, more closely matching the movement of the guppies that the students observed in the classroom fish tank. Enacting the program in the embodied model re-framed the purpose of turning for the guppies.

Ms. S: Now I see people taking one step. What I don't see is the turn. What is the first step [of the program]?

Students: Turn left.

Ms. S: You can, or you could—

Students: Turn right.

Ms. S: As long as you're staying within that line, right? So, you could go negative 90 all the way, you could go anywhere in between negative and positive 90. So, I want to see that first.

After running the embodied model for another minute, Ms. S noted that students were turning more often. Yet, students questioned the purpose of the turn:

Ms. S: I see a lot of people moving but not turning.

Student: Do we have to turn?

Ms. S: You don't have to. But go ahead and give it a shot because you—you may want—why would you want to turn? What would be the point in turning?

Students: Predator. Eating.

Ms. S: To not get eaten, or what?

Students: To get food. Eating.

Ms. S: Right, so you can look around to see if you've got anyone [representing "food"] close to you.

Enacting the model raised new questions about why the guppy might turn as it moves—not only to appear more like a real fish, but also to behave like a real fish (avoiding predators, searching for food). Thus, enacting the guppies added a new layer to students' conceptual understanding of their computational models and the ecosystems they represented. Moreover, describing turning as important for finding food or avoiding predators reframed the embodied model, positioning the model as a mechanistic representation in which agents behave like guppies, rather than an aesthetic representation in which agents only look like guppies.

In the following run, adding algae into the model raised additional questions about interactions in the ecosystem. Ms. S stopped the model as it was running because two guppies tagged the same algae. She asked, if two guppies "both walk up to the algae, and they both touch the algae, can they both eat the algae?" Ms. S intended this question to be procedural (what would happen according to the

program), but students might have interpreted the question conceptually (how would this work in a real ecosystem?). For example, Nataly said, “they should split the points”, imagining guppies sharing a fixed quantity of algae, and David began to respond, “it’s complicated . . . ” potentially considering algae as both a finite and renewable resource. Rather than sustaining the discussion, Ms. S resolved the question by answering, “sure—no—they both get their points”, and then continued running the model. Although such interactions were intended to serve as comprehension checks for understanding the embodied code, they showed their potential as opportunities to critically examine, refine, or rewrite the code to improve or extend the model based on students’ insights.

In response, by the end of this class session, as instructors, we began to position the embodied modeling activity as a reflective tool that could support discovery and exploration rather than as a rehearsal for computational modeling. In the last run of the model, Ms. S modified the code to help students consider different ways that a predator could affect the ecosystem (depending on whether it ate only guppies or it also ate guppies’ competitors):

Ms. S: The cichlid [predator] in the last one was able to only eat guppies, right? Now the cichlid can also eat killifish [competitor].

David: Ooo—I get a balanced diet.

Hunter: What?! He gets to survive so much longer!

Ashlyn: Do we think that’s going to let the guppies live longer—

Students: No!

Ashlyn: Or shorter, or doesn’t matter?

Ross: Uh, he’s going to be targeting killifish.

Reid: It doesn’t matter, either way the killi—

David: I’m gonna target everything.

Hunter: It doesn’t matter either way.

David: If it’s moving, I’m gonna eat it.

Reid: It’s not going to affect anything.

Ashlyn: Does anyone think that letting the cichlid eat the killifish will let the guppies live longer?

Students: No.

Before running the model, students could not imagine how allowing the cichlid (predator) to eat killifish (competitor) would affect the guppies. Running the model offered students insight into the dynamics of this complex interaction. After the Ms. S stopped the model, Ashlyn asked:

Ashlyn: Are there any killifish still alive?

Jasmin: I’m still alive.

Ashlyn: Just one. Last time both killifish made it to the end, now we have a killifish and two guppies still alive, so the guppies are making it longer than they did last time. Why are the guppies able to survive longer?

Jasmin: Because the cichlids are eating the killifish.

Hunter: OH WAIT! [Eating] the killifish does have an effect on it because now [the cichlids] have two prey and maybe they won’t go for the guppy as much.

Ashlyn: And so what does that mean for the guppy as well?

Hunter: That they will live longer. Some more [guppies] will live longer . . . since like David’s [cichlid] doing, he’s chasing her [killifish] which makes time for the guppies to just roam

around and find food without getting eaten straight away because he's distracted . . . then [guppies] get more food, they get more food because the killifish, there's only one instead of like three eating all the algae.

As researchers and educators, this moment helped us see the embodied model not only as a scaffold for interpreting the computational model, but as a model in its own right, that could help students notice, explore, and understand complex interactions within ecosystems. This insight led us to modify the designed activity in the following quarter to encourage students to remix the code in the embodied model to test their own ideas about this ecosystem.

3.2. Quarter Two: From Remixing to Leveraging Resources

Building on insights from quarter one, in the second cycle of the design (December 2018, quarter two), we aimed to leverage the affordances of embodied modeling for discovery and exploration. To create space for this type of engagement, we extended embodied modeling activities to two class sessions (rather than one), and we invited students to not only interpret and question the code, but also suggest changes to the code to test their ideas about ecosystems (remixing the code). We anticipated that students' insights would be related to concepts already present from their previous work with ecosystems modeling. However, as students engaged in embodied modeling, students' everyday social interactions also seeded questions, ideas, and opportunities for learning. In this section, we describe how, in quarter two, we shifted from seeing the embodied model as a student-animated version of the computational model to a medium that is more readily influenced by students' everyday resources, which might otherwise be considered outside of the bounds of the model.

3.2.1. Conceptual/Epistemic Role of Embodied Modeling

In quarter two, rather than telling the students how the embodied model's rules would change with each run, we invited students to remix the embodied code to test their own ideas about ecosystems and to alter its behavior to favor desired outcomes. Remixing was central to computational modeling in our design; when students were programming their computational models, we encouraged them to use existing code in their models as a starting point for new code, incrementally identifying changes needed in the code rather than starting from scratch. In computational modeling, remixing supported students in creating runnable code that was less likely to contain bugs—making small changes to working code enabled students to run their program after each change to identify bugs early on. Remixing served a different purpose in the embodied model; making changes to the actions and interactions in the embodied model enabled students to test the relationships between the agent-level rules and population-level outcomes, offering new insights about the model and the ecosystem that it represented.

As students enacted the embodied models, we began to recognize students' social behavior as a unique and generative resource in embodied modeling. Whereas the computational model was bounded by students' code, the embodied model was more readily influenced by "external" and potentially confounding factors, like students' social interactions. Rather than being problematic, these interactions provided new opportunities for learning as students considered the fit between these behaviors and what might happen in a real-world ecosystem. For example, from students' social behavior (standing close to friends), the location and distribution of algae (rather than simply the quantity of algae) emerged as important variables for guppies' survival. In response, several students suggested revisions to the computational model in their end-of-unit interviews. Following from these suggestions, we added "sunny spots" to the computational model in quarter three to allow students to control the location and distribution of algae (by changing the number and position of sunny spots that could support algae growth). Thus, as we began to attend to the ways that students' everyday resources shaped their participation and learning in embodied modeling, our understanding of embodied modeling once again shifted; whereas we previously saw the embodied model as a way to animate computational modeling, we began to see the embodied model as medium that

could uniquely leverage resources like students' social interactions for collaborative and dynamic sensemaking about ecosystems.

3.2.2. Significance for Learning and Participation

In quarter two, we modified the embodied modeling activities to enable students to remix the code, and we (unintentionally) created space for students' social interactions to impact the running of the model. These changes created new opportunities for participation and learning by inviting students to test their own ideas about the model and by allowing students to consider how unexpected variables, like social behaviors, might map onto the ecological phenomena represented in the model.

After the first run of the embodied model, Ashlyn invited students to make changes to the code to test their ideas about variables that might affect guppies' survival:

Ashlyn: So, we're about to switch [roles]—is there anything that we want to change that we think would make the guppies live longer?

Lucy: Maybe they could ...

Virginia: If the algae ...

Porter: If they could talk to each other.

Ms. S: Wait, wait, wait, we can only hear one at a time.

Abby: If the algae grew back up maybe a little bit faster.

Porter: If the guppies kind of communicate because I saw one thing—Ana and Virginia [guppies] were coming for the both of us [algae], but Virginia got both of us and Ana—and Virginia could have told her to go like find somewhere else because she was going to get us.

Ashlyn: Okay so guppy communication could be a solution so they could strategize better, or algae re-growing faster could be a solution. Is there any other solution you guys could think of that would make the guppies live longer?

Caleb: Reproduction faster.

Virginia: Reproduction faster.

Ashlyn: Yeah, we don't have any reproduction right now. That would be hard to imagine in an in-person model, even harder to imagine than the computer model. Any other ways we could have the guppies stay alive longer?

Lucy: They could like start with more energy.

Ashlyn: They could start with more energy. Okay so let's pick one thing that you're allowed to change in your program. Who wants to nominate something? What do you think Abby?

Abby: The algae reproduces faster.

Ashlyn: Okay so let's change in our program ... let's have the algae grow back after seven [ticks] next time. So, after seven ticks the algae will grow back. That's the only thing we are going to change this time. We might change something else next time.

In this discussion, students suggested several changes to the code that could be conducive to a desired system-level outcome: helping the guppy population survive longer. Ultimately students remixed the program to test several of these ideas, including both the algae growing faster and programming "reproduction" for the guppies.

Immediately following the discussion above, the class enacted Abby's revision to the code: after algae was eaten, it grew back faster (in seven ticks, rather than 15 ticks). On running the embodied model, the students found that this change did help the guppies survive longer. In the first run, the guppies reported that they all died after about 14 ticks, whereas with the algae re-growing faster, guppies survived for 14 to 29 ticks. In response to these data, the students concluded that with algae re-growing faster,

the guppy population could survive longer (29 ticks compared to 14 ticks). This understanding added nuance to the idea that “more producers can support more consumers”; the class found that not only the quantity of producers mattered, but also the rate at which producers could grow. Ana extended this understanding by proposing another variation on this idea. She suggested “instead of having the algae re-grow faster, it could work just as well to have the algae re-grow slower but we could have the guppies get more energy from the algae each time”. As Ana predicted, when students enacted this idea, they found that increasing the amount of energy that guppies received from algae helped the guppies survive longer. In this way, the class used embodied modeling to test their ideas about ecosystems and population dynamics, adding nuance to their understandings of these complex systems.

Throughout the class period, students took on increasingly active roles in remixing the code. Whereas in the example above, Ashlyn translated Abby’s idea about algae growth into revised code, students were more involved in negotiating how to represent guppy reproduction:

Ms. S: So, the guppies are going to reproduce. So how do we do that? We’re going to program that. How do we make that happen in the class?

Abby: After seven . . .

Lucy: Stand back up.

Abby: After five ticks the guppies stand up.

Porter: Four—four [ticks], because they get low energy, because the guppies are moving too, so you lose energy when you’re moving . . . So I said four.

Ms. S: So, reproduction is gonna happen kind of like that—respawning?

Porter: Because we have to move, so we’re gonna lose energy . . .

Ms. S: Okay so what’s the plan? So, you think after four you can stand back up? Is that what I’m hearing?

Ana: So, when we stand back up, how much energy do we have? How much energy do we get back when we reproduce? Because I wasn’t sure if it was like 10, or half of it.

Miles: 10, because you’re new.

Virginia: It’s a new guppy, so it should be the same.

Ashlyn: Okay, so another good question I heard was: can killifish also reproduce?

Students: Yeah.

Virginia: Yeah, but I think we should only have one killifish.

Porter: But the cichlids should not reproduce.

As students took on more active roles in remixing the code, they carefully considered the choices they made in the code. For example, Porter proposed that guppies should reproduce faster than algae, because guppies lose energy quickly. Deciding how to implement changes to the code helped students consider and compare how these changes might affect agents within the ecosystem as well as population-level outcomes in the model.

In addition to exploring changes to variables present in their previous models (like rate of growth or reproduction), students also discovered relevant variables that emerged from unexpected resources, like students’ social interactions. In the initial run of the model, Ms. S encouraged students to “strategically place” themselves by spreading out. Afterward, Virginia suggested that this strategy made survival difficult for the guppies:

Ashlyn: Why did all of our guppies die?

Virginia: Because all the algae was spread out.

Ashlyn: Interesting, so why does all the algae being spread out mean that the guppies are more likely to die?

Micah: Because they're going for competition.

Lucy: They have to move more.

Caleb: Because they can't move fast enough.

Porter: And if they all go for one and somebody gets it then another person won't get it.

Ashlyn: What if we had set it up to where ... we had a guppy over here, but all the algae was in the same place [across the room], would that guppy have made it?

Students: Yeah—No, No.

Ashlyn: Why not?

Ana: Because it's like, so far away, and they don't have enough energy to like go all the way.

As this discussion shows, after running the embodied model, students began to notice that the location and distribution of the algae was important. Virginia proposed that algae being "spread out" was a problem, because, as Caleb explained, the guppies could not "move fast enough" to eat the algae before they ran out of energy.

In later runs, students' social behavior offered a lens for considering the importance of the location and distribution of the algae for guppies' survival. When it was their turn to be algae, because algae did not move, students often chose to stand close to their friends (so they could talk while they waited to be eaten or to re-grow). Students noticed that this seemingly unrelated social behavior in fact affected the guppies and the ecosystem. They observed that algae "crowding" together could help some guppies and hurt others, and they then considered whether crowding, rather than spreading out, better modeled real-world ecosystems.

Ms. S: What did anyone else notice with this change?

Caleb: That the algae was like more crowded and didn't reproduce as fast—like they were more crowded in one spot kind of.

Ms. S: Okay, so how did that affect things?

Caleb: The guppies got to eat more because like Miles (guppy), he—like, every time he ate her (algae), he would like, go over there to eat something or just stand over there to wait and then come back and then wait 15 ticks and then get her again.

Ms. S: Do you think you could somehow look at that and think about animal behavior?

Caleb: Maybe that it's hungry?

Ms. S: That's good, I like that. Abby, you were about to say something?

Abby: I mean I think it might, but it also—the animals, they can't just stand still, they have to continue moving. So, I don't know if it's exactly correct, but I mean, I kind of moved between Maria, Ana, and Lucy, because they were all in a small cluster.

Ms. S: Okay, Lucy?

Lucy: So, if animals know like where the plants grow a lot, they might continue to go back to that place over time.

Ms. S: Yes, think about—okay, when you guys did the invasive models in the science class, what was one of the things that happened? Did you notice any of the agents going to a particular area?

Abby: Yeah, the zebra muss—the zebra clams or whatever, um they all went to sunny spots, and the sunny spots are where the algae would grow.

Ms. S: So, these spots over here were—where the fish were just hanging out, that could have been a sunny spot, right? That's really good.

By “crowding” together, students created an environment in which some guppies were too far from algae to survive, while other guppies thrived by circulating near a cluster of algae. In this case, social behavior that students did not intend as significant to the model (standing near friends) served as a resource for proposing and investigating a new variable in the model (the location and distribution of algae and implications for guppies’ behavior and survival). Ms. S prompted students to consider whether there might be connections between this behavior and guppies’ behavior in the real world, and she connected their current embodied modeling experience to a computational model about an invasive species (zebra mussels) that students had worked with previously. In the zebra mussel model, algae only grew in “sunny spots” and zebra mussels thrived when anchored near algae (and therefore, often near sunny spots). Thus, Ms. S built on students’ social resources and shared experiences to help students recognize a new dimension of the ecosystem (the importance of the location and distribution of organisms throughout the ecosystem). Students continued to extend this understanding throughout the embodied modeling activities. For example, when later imagining adding a predator to the model, Abby considered the role of the location and distribution of algae; she predicted that a “clump” of algae would no longer be as helpful to guppies as it had been previously, because guppies would “have to keep moving, or [predators] would get you if you stay in the same place”.

As researchers and educators, this episode helped us see students’ social behavior as potentially meaningful within the embodied model, and it helped us recognize as a generative affordance of embodied modeling the more permeable boundary between the embodied model and “outside” classroom interactions. Attending to everyday resources, like students’ social behavior, could help students identify and explore new variables in their models, and it could create opportunities to connect students’ experiences with the model’s behavior. In the following quarter, these insights led us to modify the embodied modeling activity to more explicitly invite students’ resources and experiences, including social behaviors, as well as everyday linguistic and multimodal resources that are not typically privileged in STEM classrooms.

3.3. Quarter Three: From Multimodal Resources to a Model System

In the third design cycle (quarter three, February 2019), we aimed to invite and leverage diverse multimodal and linguistic resources to support learning and participation for all students, especially students classified as ELs. To this end, we enriched embodied modeling by incorporating linked representations (e.g., gestures, student-generated language, graphs). Beyond scaffolding students’ participation in embodied modeling, leveraging multimodal student-generated resources helped students make connections to macro-level population interactions observed in their computational models, and it helped them recognize population-level patterns (e.g., the time-delayed oscillation between predator and prey populations in an ecosystem). Thus, in quarter three, the embodied model became a full-fledged component of the classroom’s system of models that could be used to explore patterns and interactions at the agent-to-agent level and at the population level.

3.3.1. Conceptual/Epistemic Role of Embodied Modeling

In quarter three, we expanded opportunities for students to leverage diverse, everyday resources in embodied modeling. For example, we encouraged students to isolate important systems phenomena from their models by inventing gestures and names for these phenomena. Naming phenomena helped students recognize and compare them across models. For example, students noticed in their computational models that when the ecosystem was relatively stable (all populations were surviving), they would see a pattern in the graph—coupled oscillations in the predator and prey populations, expressing dynamics characteristic of the Lotka–Volterra equations. When asked to describe this pattern, students often mimicked the shape of the graph (a wave) with a hand gesture. Jasper used a gesture to describe his graph during a computational modeling activity:

Ms. S: What do you notice when they're surviving long term?

Jasper: Mine have been (gesture: wave gesture, oscillatory but rising) and up, up, up. Then oxygen and carbon dioxide go up and down.

As this phenomenon became central to students' discourse, Ms. S asked student groups to nominate English, Spanish, and invented words as terms to describe the pattern, legitimizing students' everyday linguistic resources. All groups nominated at least one English term, two groups presented a Spanish term, and all groups created and justified at least one invented term. For example, Eli shared an invented term: "Flectorate. It sounds like fluctuate, and it means the rates are changing". Luis offered English, Spanish, and invented language: "We did fluctuate, balanciado, and we also made up a word. It's from balanced and graph. It's a balagraph". These examples demonstrate the wealth of linguistic resources that students brought to interpreting and describing the pattern. This activity enabled students to draw on their full linguistic repertoires to consider what was salient about the pattern, enriching their understanding of the phenomenon by offering a new way to participate in modeling. Moreover, these terms stabilized a way of interpreting the graph in the computational model, helping students recognize oscillatory regularity in other models, including the embodied model.

We further supported students in recognizing and describing key population-level phenomena by linking multimodal representations familiar from the computational model to the embodied model. For example, during the second embodied modeling day of the quarter, we created a graph (Figure 3) that mimicked the appearance of the graph in the computational model. As students were running the embodied model, Ashlyn helped one student (Nora) count and plot the number of guppies and algae alive at each tick. The graph offered students an important meaning-making resource within the embodied model; whereas students had previously relied on individual accounts of experiences to interpret outcomes in the model, the graph complemented these accounts with an aggregate view of the system. Moreover, it helped students compare outcomes across runs in the embodied model and between the embodied and computational models. Thus, in quarter three, the role of the embodied model once again shifted; by leveraging students' everyday resources and population-level representations of the model, embodied modeling became a powerful tool for making sense of agent-level and population-level ecological phenomena that could be used in dialogue with other model types.

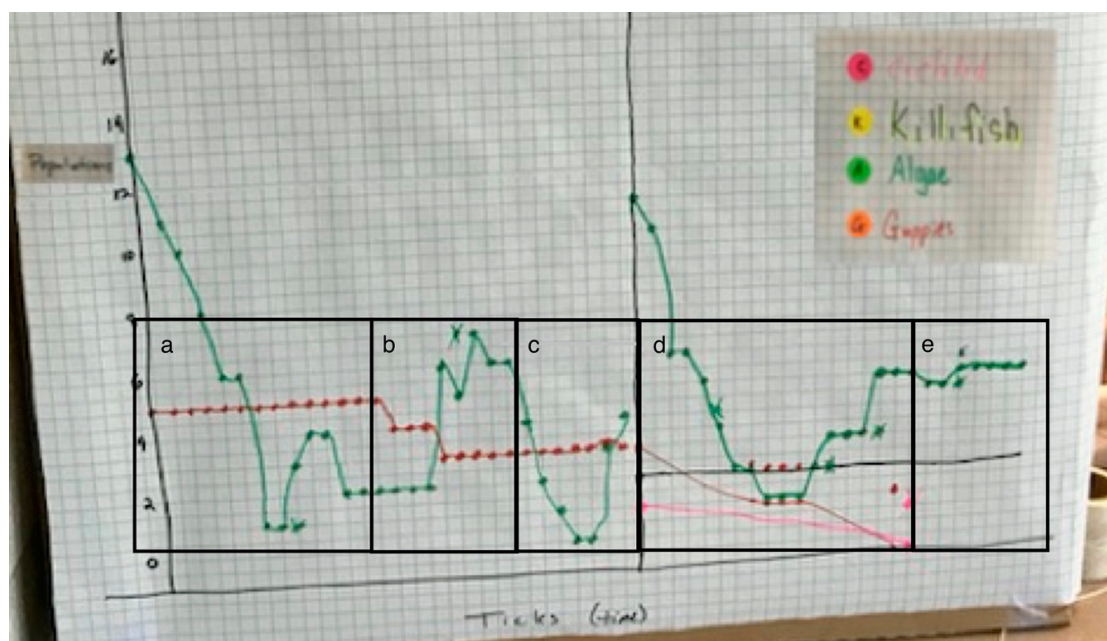


Figure 3. Embodied model graphs, used to track populations of algae, guppies, killifish, and cichlids as students enacted the embodied models. The letters a–e were added to the figure to identify segments of the graph that students referenced in classroom discourse.

3.3.2. Significance for Learning and Participation

Inviting students' resources and integrating multimodal representations expanded students' opportunities for learning and participation in embodied modeling. Specifically, these resources helped students recognize and explain population-level phenomena in the context of the embodied model and in relation to other models. Above, we described how students named key phenomena in their computational model. These linguistic resources were leveraged to help students identify the corresponding phenomena in their embodied models as well. Before the first run of the embodied model, Ms. S asked students to consider, "what would it look like to *fluctuate* in an embodied model?" After running the embodied model, Ms. S asked:

Ms. S: Did we see fluctuation?

Students: Yes, I didn't, Yes.

Amanda: It basically just went like (gesture: line with negative slope, sound: high to low pitch).

Sam: There was [fluctuation].

Ms. S: There was? Talk to me about that, Sam.

Sam: So, like with the algae, we started up higher, everyone was alive, and as we started to get tagged by the guppies, we went down. And after the 10 [ticks] we got back up ... and the guppies, they were eating food and getting more and more ... the guppies, as they were eating algae they were getting more and more energy, but then we [algae] died.

Ms. S: And so that fluctuation, what did that look like, can you show me with your hand?

Sam: (gesture: wave gesture)

Ms. S: And what is that? Which line is that? Is that the guppy line, is that the algae line?

Sam: Algae.

Ms. S: Okay can you use both hands to show me the algae and the guppies?

Sam: (gesture: wave gesture, oscillating—one hand high while the other is low)

Above, Sam used a class term chosen by the students (fluctuate) to identify a specific ecological phenomenon in the embodied model. The discussion continued as Ashlyn pushed back on Sam's use of the term, leading students to consider whether reproduction would always be helpful for a species, or if there were some cases when reproduction could be harmful (through overpopulation).

Ashlyn: Did we see that with guppies though? Did we see this shape for the guppies (gesture: wave gesture)?

Students: No.

Carlos: We [guppies] were high then we were low, low, low (gesture: stair-step gesture).

Amanda: Because the guppies can't reproduce.

Nora: They need energy from the algae.

Ashlyn: So, that's interesting, so we can see fluctuating for the guppies in their energy—for each individual guppy there is fluctuating up and down—but for our guppies over all, we just saw it decrease, because when guppies died, did they get to reproduce?

Students: No.

Ashlyn: What would happen if the guppies got to reproduce?

Eli: We [algae] would die more often then, because—

Carlos: If there's a new one that came back up—

Eli: —every 10 ticks

Carlos: and there's no more plants, every 10 ticks, it's gonna die too.

Ashlyn: That's so interesting, so you're saying that letting guppies reproduce might actually be bad for the guppies?

Jesús: Yeah, overpopulate.

Carlos: Yeah, because it's like if there's four guppies alive and there's someone [another guppy] that got back up, and there's no more plants and all of them are saying that they're dropped down, then they [guppies] wouldn't have any food, and every time they're going to have to move, and their energy would get too low.

This conversation led students to propose and test revisions to the embodied model code that represented reproduction in different ways. Thus, inventing a name and gesture for the phenomenon of stable oscillation in a population helped students identify and interrogate such “fluctuation” in the new context of the embodied model. Imagining what fluctuation would look like in the embodied model and considering how to produce this phenomenon contributed to students' understanding of ecosystems by enabling them to conceptualize and explore issues related to reproduction and overpopulation.

Incorporating the graph further supported students' reasoning about population-level phenomena. After the running the embodied model, Ms. S asked students to use their experiences to explain the graph (Figure 3a–c).

Ms. S: Alright so let's look at our data. Does anyone want to describe what they see in the data right now?

Eli: The guppies, I noticed, there was a steady state for about the first—I'm not sure how many ticks those are, but it was very steady (Figure 3a). But the algae had a rapid decline as the fish started—as the fish stayed steady, but it went back up when, I guess, one guppy died (Figure 3b). And, the—I guess it looks like two or three algae went up, and then it [algae] went right back down, after it [guppies] stayed steady (Figure 3c). So, it seemed as long as there was a guppy staying steady then the algae would go down. And then, it seemed as almost like it was very—just a little bit of change would affect it a lot, it looked like to me.

Ms. S: What else Jasper?

Jasper: It looks like this graph proves that the more predators, the less prey, and that the less predators, the more prey.

Ashlyn: Can you explain more about that?

Jasper: So, right here we have our highest amount of guppies (gesture: pointing to the graph, Figure 3a), but we also have our lowest amount of algae, and, but over here we have like a pretty high amount of algae, but we also have a low amount of guppies (Figure 3b). And this just shows that, um, there's more competition for food when there's more organisms that eat it.

Ashlyn: And so all that competition from the organisms put pressure on the algae?

Jasper: Yes.

Ashlyn: The only thing that confuses me about that then is, like, we still have a high number of guppies here (gesture: points to graph, Figure 3b), like we went from five down to four, but that's still pretty high, and we saw this big jump in algae. What do we think is happening there?

Carlos: Most of the fish, from where they were at the beginning, kept eating all the algae and making them die (Figure 3a). Um so, every time they did it, and so on the ticks from right there—it went down when it was three ticks, it went down, and then the algae went “oh, I'm

free to grow”, because all the other fish went to spread out and search for food, so then it was high (Figure 3b), went down, and went up again (Figure 3c).

Ashlyn: And so, they had a chance to re-grow?

Amanda: Also like, after like all of that decline, then there were like the 10 ticks, they started all growing—all coming back up (Figure 3b).

In this discussion, students were able to draw on their embodied experiences and memories (e.g., Carlos: “it’s from the fish—where they were at the beginning”, Amanda: “after . . . the 10 ticks, [algae] started coming back up”) to help them interpret the graph. The graph then supported students in reasoning about systemic interactions among populations at the macro-level, rather than only agent-to-agent interactions at the micro-level. For example, Eli noticed that “a little bit of change would affect it a lot”, and Jasper and Carlos used specific segments of the graph as evidence for population level interactions and trends (e.g., “the more competitors, the less prey”).

After running the model with competitors and a predator, students continued to use the graph data (Figure 3d,e) along with their perspectives and experiences to support their explanations of the system.

Ashlyn: Does someone want to try and describe what happened there?

Sean: I can see that the killifish, they were just the same throughout the whole thing—

Driana: Which one is the killifish?

Sean: The black line. The guppies didn’t do so well and also the algae was like the same with the fish, whenever it was like steady, it would drop, and then for like a second I think since also like the fish would be eating all the algae I think for, like, a second, they would all come back [algae re-grow, stand up] and then they would just be gone [eaten by guppies] after that (Figure 3d).

Eli: I noticed that as, like, in the beginning, the guppies went down, but also so did the algae, so basically what happened was that the fish started to die because, there was a lot of algae but it just took a long time for them [algae] to reproduce, and they were so spread out, so that they died and then the killifish—no cichlid, died, sort of ending the populations, both populations (Figure 3d).

Ashlyn: What happens to the algae after the guppies die (Figure 3e)?

Sam: They start rising.

Again, students used the graph to coordinate their agent-level experiences with aggregate system-level outcomes. Sean noticed that in an ecosystem with a competitor (killifish) the “guppies didn’t do as well” because together the two species of fish were “eating all the algae”. Moreover, in the discussion above, students’ observations aligned with a classic ecological phenomenon: time-delayed oscillation between predator and prey in population graphs. Rather than increasing and decreasing simultaneously, predator and prey populations oscillate in response to each other. When prey increase, predators are able to increase until they approach the carrying capacity of the ecosystem, depleting the prey. After the prey decrease, the predators also decrease, which enables prey to increase again. In this episode, students explained that because the fish ate the algae quickly near the beginning of the run, the algae all “came back” up around the same time, enabling the algae to “start rising” after the guppies initially depleted the algae and “started to die”. Thus, students used the graph in combination with their experiences to interpret population-level trends related to competition and time-delayed oscillation between predators and prey.

We conjecture that this approach to embodied modeling—building on students’ everyday language and gestures, as well as canonical resources (in this case, graphs) to represent and discuss systems phenomena—could make complex systems more accessible to all learners by legitimizing resources

beyond academic English for classroom discourse. This approach could be particularly helpful for students classified as ELs because it aligns with research in bilingual education that recommends encouraging students to access their full linguistic and semiotic repertoires for learning [8]. Data from end-of-semester interviews with students classified as ELs show that students valued this approach to modeling. For instance, Carlos (who, in the episodes above, helped interpret the embodied model and the graph) responded to the prompt, “can you tell me about the embodied model?” by explaining:

That was a really fun one, honestly, and it actually brought really good stuff at the end, because ... with the cichlids there you could know how—how they like play—how they do stuff. So, like one step, minus one energy. It’s like in real life. You move places, you lose energy. You eat something, you gain energy ... it showed different ideas because by the other models, the other models showed like just one predator, one prey—like that. That—that one had multiple—multiple preys and multiple algae things.

Carlos’s response illustrates the promise of embodied modeling for supporting learning and participation for students classified as ELs. Carlos described the embodied model as making visible agent-level behaviors also represented in the computational model (“one step, minus one energy”), and he also saw the model as relevant to “real life”—“you move places, you lose energy”. Moreover, he positioned the embodied model as uniquely useful for understanding systems because unlike students’ previous models (e.g., drawings, food webs, physical models), the embodied model had “multiple preys”, not just “one predator, one prey”. Although we recognize that Carlos is not representative of all students classified as ELs, we see his engagement in embodied modeling as an indication of how embodied modeling could shift learning and participation by creating a multimodal interactive learning environment, as recommended by bilingual education research.

4. Discussion

Through iterative cycles of design and analysis, our understanding of the embodied model’s potential for supporting learning and participation shifted. In quarter one, we recognized the embodied model as a reflective tool that supported more equitable participation by inviting and relying on all students’ contributions and perspectives for meaning-making. In response, in quarter two, we framed embodied modeling as a way for students to test their own ideas about ecosystems, positioning the embodied model as a tool that the students, and not only the instructors, had the authority to modify. We also noticed that students’ social resources shaped the model in unanticipated, yet productive ways (e.g., considering the role of the location and distribution of producers in the ecosystem). Building on these findings, in quarter three, we further expanded the range of resources recognized and valued in embodied modeling by integrating multimodal representations and students’ everyday resources (e.g., graphs, gestures, student-generated language). As a result of these design revisions, with each design cycle, embodied modeling afforded students new opportunities for learning and participation as they increasingly leveraged a wider range of resources and explored new ideas through embodied modeling. From the perspective of a network of classroom models and modeling experiences, embodied modeling shifted from being a subservient support for computational modeling to becoming a full-fledged member of the multimodal model system, and it played a central role in our instructional strategy to invite a wider range of sense-making resources into modeling.

These findings have implications for the design of equitable STEM learning environments for all students and for students classified as ELs in particular. We conceptualize science learning as “learning to participate appropriately” in a scientific community [64]. A “scientific community” is a group of people with shared values and tools and a shared purpose: creating scientific knowledge [64,65]. Science practices include forms of discourse—ways of expressing ideas, including talk, gesture, writing, and visual and material representations [52,53,66]. Such discourse practices allow scientists to communicate and collaborate, and they offer scientists generative perspectives of phenomena [51,53]. Yet, because “appropriateness” is defined by the dominant community, discourse practices that are

considered “appropriate” can also be oppressive [67]. For example, the English-only norms in discourse practices common in U.S. classrooms limit multilingual students’ opportunities to leverage their full linguistic repertoires. Moreover, an emphasis on academic English limits all students’ opportunities to leverage multimodal representations for sensemaking in science. Instead, research emphasizes the importance of leveraging students’ linguistic and representational practices in science education [68,69]. With each iteration of our design, we refined our framing of embodied modeling activities to create more opportunities for multimodal sensemaking for students, positioning its more accessible modalities not as mere scaffolds toward appropriate participation in science practices, but rather as means to develop multimodal representational assets that contributed to the classroom’s understanding of complex phenomena. We did this first by inviting students to remix code, and then by leveraging multimodal resources including students’ language, gestures, and social interactions. In this sense, each design iteration expanded the range of legitimate resources available for “participating appropriately” in STEM practices. These changes to the role and nature of embodied modeling created more equitable opportunities for learning, enriching students’ understanding of complex systems as they represented ecological phenomena in new ways and, in turn, developed increasingly nuanced, networked systems of models to capture their emerging understandings of ecosystems.

Broadly, our findings demonstrate the potential of embodied models to serve as full-fledged components of a classroom’s system of models for making sense of a complex phenomenon. In prior research, embodied models have often been directly linked to computational representations. This approach can scaffold students’ understanding of complex systems as students take on the perspective of agents and experience system-level emergent outcomes [27–30]. However, this approach also can limit students’ opportunities for making sense of the relationships between embodied and computational representations. In contrast, in our design, students negotiated the relationships between their computational and embodied models through classroom discourse. For example, considering what “fluctuate” (a student-generated term developed in response to the computational model) would look like in the embodied model helped students develop a deeper understanding of population dynamics and of modeling; mapping across representations helped students identify and describe key concepts (e.g., oscillation between predator and prey populations) and consider the similarities and differences between computational and embodied representations of a phenomenon, an important disciplinary practice [11,70]. In addition to comparing models, our design created opportunities for students to engage more fully in the practice of modeling; students not only participated in and reasoned with the embodied model, they also refined the model by remixing the code. In this way, our design re-framed embodied modeling activities, which primarily have been positioned as tools for conceptual learning or as scaffolds for computational thinking. Positioning the model instead as a tool that students can extend and refine to test their own ideas shows potential for increasing students’ epistemic control in classroom inquiry [71].

In addition, these findings have implications for supporting students classified as ELs in STEM classrooms. Inviting and leveraging students’ meaning-making resources shows promise for disrupting the monolingual ideologies that permeate schools [72,73], particularly in classrooms with both multilingual and monolingual students. In these contexts, multilingual students may be reluctant to use languages other than English if they do not see these languages as part of the “academic” language valued in school or are concerned about distancing themselves from monolingual peers [74]. In U.S. schools, English has been privileged as an “unmarked” or normative language; yet, research demonstrates that in hybrid spaces in which students’ everyday linguistic resources are also unmarked, students’ resources can mediate disciplinary practices and learning [75]. Learning environments that legitimize students’ full linguistic repertoires, as well as multimodal resources, could help classrooms become spaces that value diverse forms of expression, contributing to more equitable learning opportunities for students classified as ELs [76]. Moreover, such an approach could be beneficial for all students; beyond linguistic resources, attending to cultural heterogeneity in students’ sensemaking and participation is fundamental to learning [77,78] and can help address historical and systemic barriers experienced by students from non-dominant groups in STEM classrooms [79,80].

Our data demonstrate that expanding the role of students' ideas and resources in embodied modeling activities can create new opportunities for learning and participation. Still, there is much to learn about designing to support inclusive science practices, particularly in linguistically diverse classrooms. Our study is susceptible to the weaknesses and limitations of design research [81], particularly in terms of generalizability and scale. One way that we have attempted to address these concerns is with a thick description of our design and of classroom interactions, providing a foundation that researchers and educators can explore and adapt in relation to their own specific contexts. We also recognize that most K-12 classrooms do not have access to the resources available in this study. For example, we relied on having two instructors, Ms. S and Ashlyn, to plan, facilitate, and debrief embodied modeling activities, providing students with more feedback and support than is typical in K-12 STEM classrooms. While we believe that our designs for embodied modeling activities could be productive in other classroom contexts, further research is needed to explore approaches that cultivate students' resources and leverage multimodal representations as part of STEM learning.

5. Conclusions

This paper advances learning theory by illustrating the potential of embodied modeling for supporting complex systems learning. Through iterative cycles of design and analysis, we have shown how embodied modeling activities can invite and leverage students' diverse ideas and representational competencies as generative resources for sensemaking. This approach to embodied modeling can inform the design of learning environments that support students in reasoning about complex systems and investigating their emergent behaviors. To realize this potential, further work is needed to address persistent and dominant ideologies that privilege “academic” English in STEM classrooms. While it is difficult to shift disciplinary ideologies and values, this work is critical for creating more equitable opportunities for learning and participation in STEM.

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Appendix A. Embodied Modeling Programs

The programs below represent the embodied “code” presented to students for each agent (algae, guppy, killifish, cichlid); however, the programs were modified by students throughout the course of the embodied modeling activities. Students were also given an “energy log” (Figure A1) to track their energy. “Ticks” were used to measure time. At each tick, all of the agents in the model ran through the steps in their program one time; then, the tick ended. The instructors (Ms. S and Ashlyn) used a bell to mark the beginning of a new tick. They rang the bell, waited for students to finish running through their programs, then rang the bell again until the model was paused or stopped.

Energy Log

Tick number	My energy	Tick Number	My energy
1.		41.	
2.		42.	
3.		43.	
4.		44.	

Figure A1. Energy log given to students to track energy lost (from moving) and gained (from eating).

Appendix A.1. Algae

Start by standing up in a random location.

For each tick:

If you are tagged by a predator:

You have been eaten (sit down).

After 10 ticks, you can stand up (you have grown back as new algae).

Appendix A.2. Guppy

Start by standing up in a random location, facing a random direction.

Write “10” for *My energy* for tick one.

For each tick:

Pick a number in between -90 degrees (full left turn) and 90 degrees (full right turn). Turn that amount.

Take one step forward.

Subtract one from your energy and **on the next line** write your new energy

If your energy is zero:

You have died (sit down).

If you are within arm’s length of algae:

Tag the algae

Add two to your energy and **on the same line** write your new energy

If you are tagged by a predator:

You have died (sit down).

Appendix A.3. Killifish

Start by standing up in a random location, facing a random direction.

Write “10” for *My energy* for tick one.

For each tick:

Pick a number in between -90 degrees (full left turn) and 90 degrees (full right turn). Turn that amount.

Take one step forward.

Subtract one from your energy and **on the next line** write your new energy

If your energy is zero:

You have died (sit down).

If you are within arm’s length of algae:

Tag the algae

Add two to your energy and **on the same line** write your new energy

If you are tagged by a predator:

You have died (sit down).

Appendix A.4. Cichlid

Start by standing up in a random location, facing a random direction.

Write “10” for *My energy* for tick one.

For each tick:

Pick a number in between -90 degrees (full left turn) and 90 degrees (full right turn). Turn that amount.

Take one step forward.

Subtract one from your energy and **on the next line** write your new energy

If your energy is zero:

You have died (sit down).

If you are within arm’s length of a guppy:

Tag the guppy

Add two to your energy and **on the same line** write your new energy.

Appendix B. Interview Protocol

1. Shows a picture of each of the students’ models: plant investigation, biosphere plan, biosphere model, food web, embodied model, computational model. For each model, ask:
 - a. Can you tell me about making this model?
 - b. What does this model show?
2. Are any of the models related to each other? Why or why not?
3. Which of the models were the most interesting or helpful to you?
4. Which of the models were the least interesting or helpful to you?
5. Did you use different languages [representations] in your models?
 - a. If yes: does using different languages [representations] change how you think?
 - b. If yes: can you tell me about a time when that happened?
6. In your science class, we used a computational model about zebra mussels. But we didn’t build that one—it was already built.
 - a. If you think about the scientists that built that model, what kind of information do you think they needed to build it?
 - b. How do you think they get that information?
 - c. Do you think those scientists use other models to understand zebra mussels?
 - i. If yes: which types of models? How would they use them?
7. Is there anything we should definitely keep or definitely change about these projects for next quarter?

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