Journal of Science Education and Technology (2020) 29:53–64
https://doi.org/10.1007/s10956-019-09801-y

Integrating Computational Thinking into Elementary Science Curriculum: an Examination of Activities that Support Students' Computational Thinking in the Service of Disciplinary Learning

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Published online: 22 November 2019
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Abstract
Using an example of a grade 3 science unit about population changes during competition for resources, we describe how we integrated computational thinking (CT) into existing curriculum identifying three levels of depth of integration: identifying connections that already exist, enhancing and strengthening connections, and extending units to include activities that more explicitly develop students' CT. We discuss students' understanding of the relationship between a simple model of an ecosystem and the actual phenomenon it represents, their engagement with the unit's data-gathering and data analysis activities, their ability to engage in sense-making regarding data they generated and analyzed, and how collectively the study supports their understanding of the complex system. This example module is part of "Broadening Participation of Elementary School Teachers and Students in Computer Science through STEM Integration and Statewide Collaboration," a National Science Foundation-funded collaboration among Massachusetts teacher educators, researchers, teachers, and state-level education administrators that developed and implemented a number of elementary grade, CT-integrated science and mathematics curriculum modules. Collectively, these modules are designed to develop practices related to several key CT topics: abstraction, data, modeling and simulation, and algorithms. These CT topics support the development of core skills related to, but not exclusively the domain of, computer science. The strategy of integrating CT into core elementary STEM subject areas was intended to cultivate CT practices in support of science learning.

Keywords Computational thinking · Elementary · Science · Models · Simulations · Data

Introduction

The Broadening Participation of Elementary School Teachers and Students in Computer Science through STEM Integration and Statewide Collaboration project ("Broadening Participation") is a collaboration among curriculum developers, classroom teachers, researchers, and state-level administrators, designed to address the challenge of making CT a regular part of every child's school day. EDC, in partnership with the Massachusetts Department of Elementary and Secondary Education (DESE), worked with over 60 teachers and administrators from 15 school districts across the state of Massachusetts to create CT-enriched science and mathematics units for grades 1–6 by adapting existing teacher-written units that had been curated by DESE. Our goal has been to create materials that develop CT skills and practices within disciplinary contexts while also supporting the learning in the underlying discipline. Each integrated module (I-Mod) was tested, revised, and refined in an iterative process, and the resulting materials are available through DESE, along with additional resources for integrating CT into science, mathematics, and other disciplinary instructions.

What Do We Mean by CT?

We based our work, and our definition of CT, on the Massachusetts Digital Literacy and Computer Science (DLCS) Framework (Massachusetts Department of Elementary and Secondary Education 2016). Massachusetts was one of the first states to elevate expectations for K–12 students' engagement with digital literacy and computer science. The DLCS framework, in turn, was based on previous work by a number of organizations, including the College

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Board, the Computer Science Teachers Association (CSTA), and the International Society for Technology in Education. The DLCS Framework identifies five topics within the CT strand:

- Abstraction
- Algorithms
- Data
- Modeling and simulation
- Programming and development

We focused on developing science and mathematics materials that integrated the first four of these topics. We did not focus on programming largely because other groups of educators were already addressing this area through stand-alone coding experiences for elementary students. Additionally, we observed early on in the project that few students had enough prior experience and knowledge about programming, even the unplugged variety, to productively coordinate both their science and mathematics learning with further learning about programming. In looking for ways to integrate CT into existing science and mathematics instruction, we wanted to create learning opportunities that would call on elementary students' CT without potentially impinging on their engagement with target concepts within the core subject area.

Motivation: Why Integrate CT into Disciplinary Content for Elementary Students?

High schools and, increasingly, middle schools in the USA offer stand-alone computer science courses and rely on programming within these courses to develop students' CT. This strategy is less likely to be widely adopted in today's elementary schools; the instructional day is already filled to capacity (and beyond). Rather than introduce computer science as another required discipline into the elementary curriculum, many elementary educators are exploring ways to integrate CT skills and practices that are foundational to computer science (and also more generally useful as a cognitive tool) into instruction in existing disciplines. There are several benefits to this approach:

- By integrating CT into existing subjects, teachers are more likely to find instructional time to explore CT concepts (and to feel less overwhelmed by the idea of taking on wholly new instructional responsibilities).
- While educators often turn to coding activities as contexts for developing CT, CT shares much in common with problem solving in other disciplines. Integration allows elementary teachers to exploit the substantial overlap between CT and important skills and practices in other subject areas. For instance, CT is referenced explicitly as an important science and engineering practice by the Next Generation Science Standards (NGSS) and also figures heavily in other core science and engineering practices identified by NGSS (NGSS Lead States 2013).
- Taking the approach of integrating CT into math and science instruction allows the core subject area curriculum to do double duty: deepen students' disciplinary understanding while also facilitate the development of students' CT practices and skills.

Identifying Contexts for Integrating CT

We began by working with teachers to identify those previously developed units that provided promising contexts for integrating CT, consulting both the CSTA Standards (Computer Science Teachers Association 2017) and the Massachusetts' DLCS (Massachusetts Department of Elementary and Secondary Education 2016), as well as the computational thinking in mathematics and science taxonomy described by Weintrop and colleagues (Weintrop et al. 2016). However, we tried to avoid modifying these units with activities that did not, at the same time, reinforce or further students' science and mathematics learning. For example, in a geometry unit, we found that fourth grade students were not familiar enough with the mechanics of block-based coding to be able to use a coding activity to explore ideas related to angles and angle measurement.

Three Levels of CT Integration: Exist, Enhance, and Extend

We characterize our efforts to adapt the original teacher-written materials by the following three levels of CT integration (Waterman et al. 2018).

1. CT concepts, skills, and practices already *exist* in the lessons and can simply be called out or elaborated upon (mostly for the teacher). These opportunities for CT may not involve direct engagement with technology, but teachers can point out examples of how they can also relate to computers or other technology. We felt this first level was important to acknowledge, as it helps teachers recognize that they were already, in part, developing CT when they were teaching science and mathematics. For example, a typical inquiry-based science activity may have students use or create a physical model to understand a particular phenomenon. We might encourage teachers to link this existing activity to CT concepts by leading a general discussion about models, such as what a model is, how it represents the phenomenon, which key features and attributes are included in the model, and which are left out.

2. Creation of additional tasks or lessons to *enhance* the disciplinary concept and provide clear connection to computing concepts that are present, but not central, to the existing lesson. For example, a typical lesson may have students gather data on their own, create a visual representation by hand, and analyze their data. CT enhancement activities might be to plan a strategy for data collection on a larger scale and use spreadsheets to log, organize, and create representations of the resulting data set for further analysis.
3. New lessons or sequences of lessons that *extend* the disciplinary concept as a basis for CS exploration, likely involving programming activities. For example, students use a computer simulation and modify variables or underlying code to investigate how dynamic systems change over time, leading to a richer understanding of the system.

This framework offered a structure for the development team, including our teacher partners, to identify opportunities for integrating CT. It helped us to find and highlight overlaps among concepts and practices in science, mathematics, and CT while also encouraging us identify and develop currently unexploited opportunities for delving more deeply into CT.

The remainder of this paper uses the example of the development and implementation of one grade 3 I-Mod, "Survival of Organisms," to explore design decision and students' engagement with CT.

Developing the I-Mod for Grade 3 Study of Populations: the Design Process

The development of this I-Mod began with the work of a team of third grade teacher collaborators from one of the participating elementary schools. As part of a previous project, MA DESE developed a collection of "model curriculum units" (MCUs) for MA teachers. The teachers reviewed the third grade science MCUs in light of the NGSS and DLCS standards and chose a unit titled "Survival of Organisms." As originally written, this unit addressed two essential questions: (1) "What happens to the survival of a population if it cannot meet its needs with the resources available?" and (2) "How big of a change to the environment causes an organism to go extinct?" With support from project staff, the teachers' task was to revise the MCU into an integrated CT-and-science module (I-Mod), identifying opportunities in the original unit where integrating CT would be appropriate (Fig. 1). The result was an expanded set of activities for the original unit which third grade teachers could use whenever they taught students about interdependent relationships in ecosystems (NGSS Lead States 2013).

Addressing Grade 3 Standards

Teachers and project staff reviewed relevant standards in relation to the existing MCU. NGSS makes explicit reference to analyzing and interpreting data as being an essential science and engineering practice. Moreover, embedded in several areas within the NGSS content standards are descriptions of collecting and interpreting data within specific scientific topics. For grade 3, three standards include mention of using data to promote conceptual understanding, two in Life Sciences and one in Earth Sciences. While only these content standards explicitly refer to data representation and analysis for grade 3, the practice of using data to understand science concepts and phenomena is, of course, fundamental to the whole of science. Moreover, the Common Core State Standards for Mathematics (CCSS-Math) include several standards for measurement and data that also involve gathering and interpreting data, including drawing a scaled bar graph to represent a data set (National Governors Association Center for Best Practices and Council of Chief State School Officers 2010).

There is considerable overlap between the treatment of data in both NGSS and CCSS-Math, as well as the computer science standards around data collection, representation, and analysis (Computer Science Teachers Association 2017). The analysis of these standards, then, became the foundation onto which we applied the exist/enhance/extend framework for developing the I-Mod.

A Promising Activity for Integration

The original MCU was designed to address two essential questions: (1) "What happens to the survival of a population if it cannot meet its needs with the resources available?" and (2) "How big of a change to the environment causes an organism to go extinct?" One activity in the original unit was adapted from the *Oh Deer!* game from Project WILD (1992). This source activity was designed to provide an experience that helps students explore that first essential question by having students engage in a game that includes three key resources animals need for survival (food, water, shelter) and simulates the competition animals may experience in finding them. Variations on the game introduce predators (wolves) and meteorological events that can interfere with the availability of certain resources (such as a drought or a hurricane).

This particular game proved to be the most fertile ground for incorporating CT into the existing unit. As developed by Project WILD, the *Oh Deer!* game is a physical simulation that represents a highly simplified model of the components of a local ecosystem. We were able to leverage the game as a basis for (a) exploring aspects of the model, (b) thinking about the computational aspects of the model and the data it could generate, and (c) deepening the analysis of the generated data. The

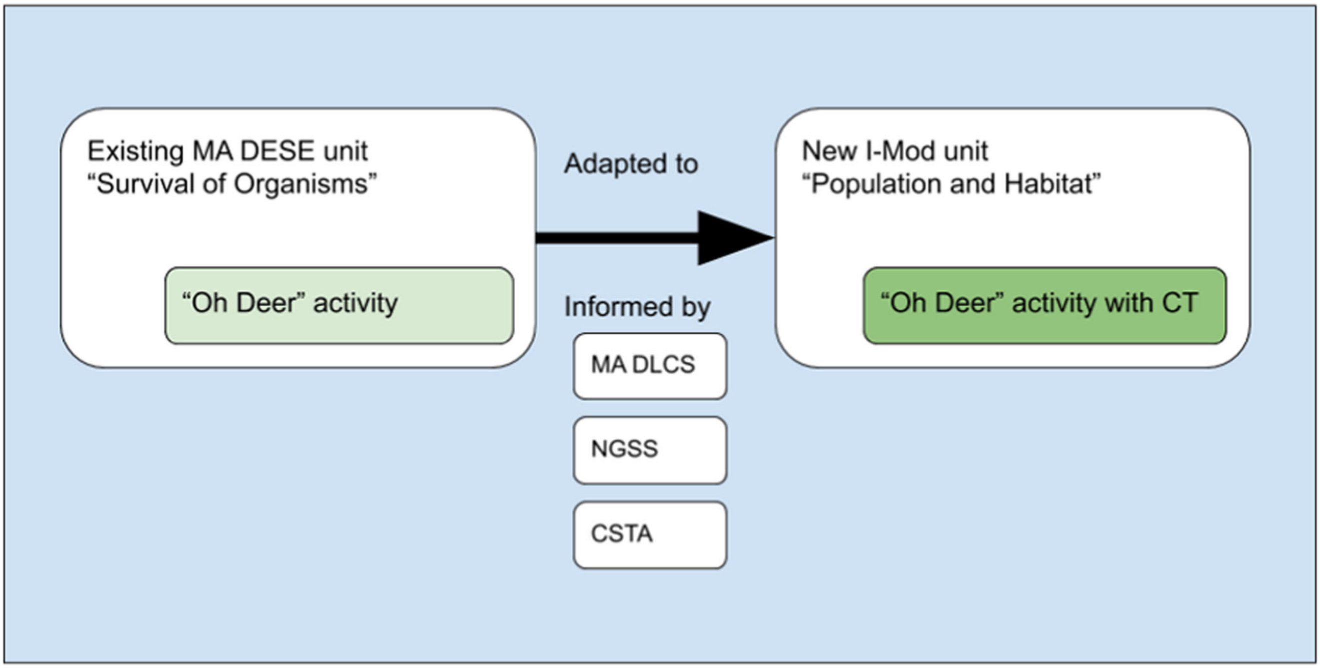

Fig. 1 Process of creating I-Mods

resulting I-Mod added two key activities that deepened the CT by enhancing and extending the existing embodied simulation: (a) enhancing the discussion and debrief around the game by adding call-outs to teachers identifying CT connections inherent in the game itself, such as how scientists might develop a model of an ecosystem to generate simulated data and analyze that data to better understand how changes in local habitat might affect the deer population, and then (b) extending the specific example to consider the interplay between the various populations within an ecosystem by studying the graphs resulting from multiple runs of a spreadsheet simulation that generated data over a 100-year time span instead of the 15–20 years typically captured through the physical game. Table 1 provides a brief summary of the levels of CT integration we undertook during development of this I-Mod.

Integrating CT by Exploiting Existing Connections

Because the *Oh Deer!* activity in the original MCU focused on building and acting out this model, and examining the data generated by the game, components of CT that already existed in the unit included modeling and simulation, data, and abstraction. The *Oh Deer!* activity is essentially a model of how changes in habitat affect a species (deer) and the interdependencies among populations in an ecosystem. It is intentionally narrow—in abstracting out only the relationship between one predator, one prey, and three resources, it omits many other factors that impact the relationships among organisms within an ecosystem. Thus, abstraction is an element of CT that already exists in the activity. While simple, the model offers an entry point for young students just beginning to understand an ecosystem's dynamic relationships. This process of beginning with a relatively simple model and gradually folding in more complexity to better account for the system under study is common practice in STEM fields.

In the original MCU, students also collected and graphed the data generated by the game. While the source materials make no use of technology for examining the data, the methods for collecting and graphing the data provide a preliminary step toward richer CT aspects of the data topic.

Integrating CT into an Existing Unit by Enhancing Current Activities

The first enhancement we made was to add information and discussions to the teacher support materials to make these CT connections more explicit. We suggested questions for class discussion that encouraged students to explore the role of models and simulations in understanding systems. Primary was the suggestion to emphasize that, while the activity may be considered a game, students were engaging in acting out a model representing deer and their habitat. This distinction was reinforced by including additional prompts such as the following:

- Identify the critical elements in the game (populations and their interrelationships)
- Identify simplifications in the game (e.g., each deer only selected a single resource type in any round)
- Identify elements that were not included in the game (e.g., competition by other species for resources, other threats to resources such as weather).

Table 1 Integrating CT into the original MCU

	Exist	Enhance	Extend
Abstraction		• Think about what aspects of an actual habitat are represented as key elements in the game and how it had been simplified.	• Describe the modeling and simulation of a habitat
Automation			• Describe the modeling and simulation of a habitat • Demonstrate the simulation of an ecosystem
Experimentation			• Demonstrate the simulation of an ecosystem
Modeling and Simulation	• Embodied experience of a simple model of a habitat and habitat changes on a population	• Think about aspects of a model to include in a computational model	• Describe the modeling and simulation of a habitat • Run simulation experiments
Data Gathering & Analysis	• Record data during the game • Graph data Use data to describe changes in deer population as habitat components changed	• Deeper analysis of generated data to explore patterns of change in deer and resources • Teacher demonstrates how to use Excel to record data and generate different kinds of visual displays	• View and analyze simulation-generated data • Compare simulation generated data to data generated through Oh Deer! game • Use simulated data to reason more generally about dynamics within an ecosystem

Next, we expanded on the use of data for investigating the effect of changes in habitat on the deer population and the interrelations among resources, deer, and wolves. We enhanced this activity to include using a spreadsheet to enable multiple ways of representing the data collected and to compare the dynamics of the three populations. In addition to facilitating students' discussing the results of the game themselves, teachers engaged students in a discussion about the advantages of the different representations for seeing patterns in the data and making conjectures and predictions about population dynamics and interdependencies.

Integrating CT by Extending the Exploration with a Digital Model

We developed a spreadsheet model of the *Oh Deer!* game to introduce the idea that computer-based models make it possible to explore phenomena in ways that are not always possible or feasible. In this case, the spreadsheet model provides a mechanism for generating multiple sets of simulated data both with larger populations and longer periods of time than would be possible only by collecting data from a classroom of students playing the game. The rationale was to promote the idea that certain patterns would still emerge, even if the data were completely different from one game to the next, because of the same underlying relationships among the populations. The key part of the model is in how, for each round, it "decides" how many resources are of each type, and independently, how many deer seek each of the three types of resources. One can even build into this model the catastrophic events described above by zeroing out the available water resource to simulate a drought, or greatly reducing the shelter resource to simulate a flood or forest fire.

While the underlying mechanics of this spreadsheet are too advanced for grade 3 students, the simple introduction and exploration of the spreadsheet's outputs does familiarize young students with the potential power of digital tools and their usefulness to scientists.

I-Mod Implementation and Students' Learning

The I-Mod was piloted by grade 3 teachers from the development team, revised by project staff, and then taught again by a combination of those original teachers and a new cohort of teachers. At most schools, teachers played the game only within their own class. At one school, however, five teachers combined their classrooms, totaling over 100 students, to play *Oh Deer!* outside in the playground.

Activity 1: Modeling the Ecosystem and Generating Simulation Data

Students start the lesson by discussing the resources deer need to survive in their habitat. In this particular model, the focus is on three key resources: food, water, and shelter. Students are then introduced to the rules of the *Oh Deer!* game and the class is split roughly in two. One group represents resources, and the other group deer. At the start of each round, students face away from each other. Each student in the resource group secretly decides which type of resource they will represent (food, water, or shelter) using hand symbols: hands on stomach means food, hands over mouth means water, and hands touching overhead means shelter. At the same time, each student in the deer group secretly decides which resource they will seek in the round using the same hand symbols.

When the teacher says "go," all students turn around so the resource line and the deer line face one another. Each deer tries to pair up with the resource it seeks (Fig. 2). Each student follows their own particular rule:

- A deer that finds the resource it seeks consumes it and survives. That student will be a deer for the next round.
- A deer that does not find the resource it seeks dies. That student becomes a resource in the next round. (Teachers may describe this as the deer decomposing and becoming part of the resources.)
- A resource that is consumed by a deer will no longer be a resource (because it was consumed). That student will become a deer in the next round, because the healthy deer was able to reproduce.
- A resource that is not consumed by a deer remains a resource.

After some number of rounds (generally 5 or 10), a wolf is introduced to the habitat (Fig. 3). During a round, each wolf can eat one deer. Any wolf that is unsuccessful at finding a deer dies and becomes a resource for the next round; any wolf that finds a deer lives and reproduces, and both students are wolves in the next round.

At the end of each round, students tally the number of wolves, deer, and resources. In some classes, the teacher will record the count on the board. In others, some students are designated the "biologists" and record the counts in their data collection sheets (Fig. 4).

To reinforce the connection to computational thinking, teachers remind students that they are not just playing a game, but that they are conducting an experiment, acting out a model of an ecosystem in order to generate data they can study later. Teachers revisit this idea as they debrief the activity later.

Fig. 2 Deer looking for matching resource

Fig. 3 Wolves enter the fray

Part of what we want students to understand is that any model is an abstraction that includes some elements of a phenomenon and discards other ones, either because they are less important or not central to the specific aspect of the phenomenon being studied. Therefore, it is important for teachers to consider the components of the model with students, asking them how the model is like what actually happens in nature and where it falls short. Such a discussion is aimed at students' having a better understanding of the complexity of

Oh Deer! Data Collection Table Form 1

Round	Deer	Resources	Wolves
0	12	9	
1	14	7	
2	18	3	
3	6	15	
4	8	13	
5	16	5	
6	8	13	
7	16	5	
8	12	9	
9	16	5	
10	8	13	
11	14	6	1
12	12	7	2
13	12	5	4
14	8	9	4
15	10	3	8
16	2	5	14
17	2	15	4
18	2	17	2
19	4	17	0
20	8	13	0
21	10	11	0

Grade 3 Science — Populations and Habitat
Lesson 2: *Oh Deer!*: Modeling a Habitat
Data Collection Sheet Option 1

Fig. 4 Data collection sheet

interrelatedness in any ecosystem, of how using the model to focus on a smaller subset of ecosystem components can help begin to build understanding of the larger whole, of some of the cause-and-effect relationships among these components, and of the pitfalls of taking simulated data as a complete representation of the underlying phenomenon.

Working with a model in this way provided students with an exercise in understanding complex systems, one of the CT integration practices described in Malyn-Smith and colleagues (Malyn-Smith et al. 2019)—in this case, the population dynamics within an ecosystem. The model the students were building is actually a good representation of an agent-based model: each student is an individual, independent agent with a strict set of rules, and the dynamics of the system is modeled as each agent makes its choice (randomly) and interacts with other agents in the system.

Another key part of this activity is collecting data. During pilot testing, we observed a number of students struggling with how to organize their data; the revised materials offer several options for teachers to use (from graphic organizers to preprinted tables to blank science notebooks). For schools where multiple classes may be implementing this I-Mod, each class could engage in the game separately, generating their own data. Then, during the analysis activity, students can combine the various classes' data. Such an organization would help support the idea of students engaging in collective sense-making, another CT integration practice.

Even as the simulation was underway, some student data collectors were beginning to use their data to make sense of the interactions, predicting changes in the populations and thinking about the interconnections among resources, deer, and wolves. Some students engaged in discussions that exhibited their understanding of the potential consequences of actions, another CT integration practice. Here is an excerpt of an unprompted discussion between two students (Fig. 5), with the teacher encouraging and helping facilitate sense-making.

Fig. 5 Two boys talking

At the time of their discussion, there were 32 wolves, 36 deer, and 40 resources on the field; student 2 is predicting what will happen in the next round of the simulation.

Student 1: All the wolves will take all the deer and the natural resources away.
Student 2: No, but all... mostly all the wolves will die.
Student 1: How will they die if they have to take people to be a wolf?
Student 2: A lot of them will die. Only eight wolves will get it [a deer], and the rest will die.
Student 1: What?
Student 2: Only eight wolves will get to eat ... the deer. And that means a lot of the wolves are going to die.
Teacher: So what's going to happen at the end of this round?
Student 2: There's going to be no more deer
Teacher: Most of the deer will get eaten, but there will be a whole lot of wolves, and only a couple of deer. Then what will happen?
Student2: Next round, a lot of the wolves are going to die because there will be only eight deer.

Student 2 appears to be connecting facts about animal survival with the underlying mathematics of the situation—the wolf population cannot continue to grow unchecked because its numbers will ultimately overwhelm the deer population. Then, in a future round, with no (or very few) deer left, the wolves will have nothing left to eat. Student 2 recognizes that the number of wolves that can survive an upcoming round of play cannot be more than the number of deer that will be available for them to catch—and that this number is determined by the current round of play. It is not clear from this exchange whether the student recognized a generalizable relationship or was reasoning about the specific instance, but observations such as these provide opportunities for teachers to help students make generalizations during follow-up discussions.

In the class discussion following the activity, students talked about their impressions of the game. In one teacher's class, some students observed that there must have been "cheating" going on, justifying their conclusion by describing anomalies in the data. For example, in one year (round of play), the deer population was 8, and the next, the population was 19. Students were able to make the argument that the data did not make sense given the rules of the game; they recognized that there should have been no more than 16 deer in that next year and that the additional 3 deer were probably not a counting error. Students went on to debug the activity, providing suggestions to ensure that rules are followed (such as providing colored popsicle sticks to declare what type of resource the student chose as opposed to relying on students not to switch their type in order to pair up with a "deer friend").

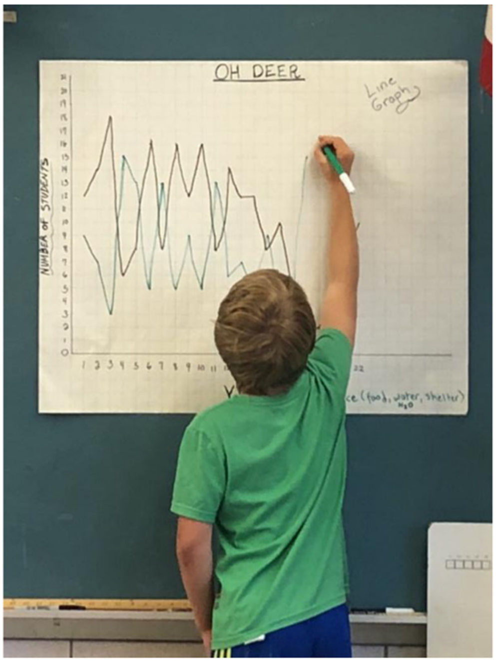

Fig. 6 Class-generated representations of Oh Deer! data

Activity 2: Representing and Analyzing Data

Students graphed by hand the class data generated during the game (Fig. 6). Then, the teacher entered the data into a spreadsheet and demonstrated how technology allowed them to quickly generate a chart of their collected population data similar to the one in Fig. 7. The teacher led a class discussion asking students to describe and analyze the patterns they saw in the chart.

Students made observations such as "both the blue line and the orange line go up and down" and "the blue is like the orange line, only upside down, at least at first." These observations led the class to consider interdependencies of populations, such as the following:

- when the resources were low one year, the deer population would go down the following year because they wouldn't have enough resources to survive
- when the deer population was low one year, the resources would go up the following year because fewer deer were around to consume the resources.

Students also discussed the possibility of local extinction of the deer, and the effects that such an event would have on the resources and the wolves in the ecosystem. In several classes, this lesson was part of a larger unit on extinction, and the discussion of the possibility of local extinction became a springboard for talking more broadly about extinction.

Activity 3: Using a Complex Model

We extended the lesson to include working with a more complex spreadsheet-based model built to reflect the same rules

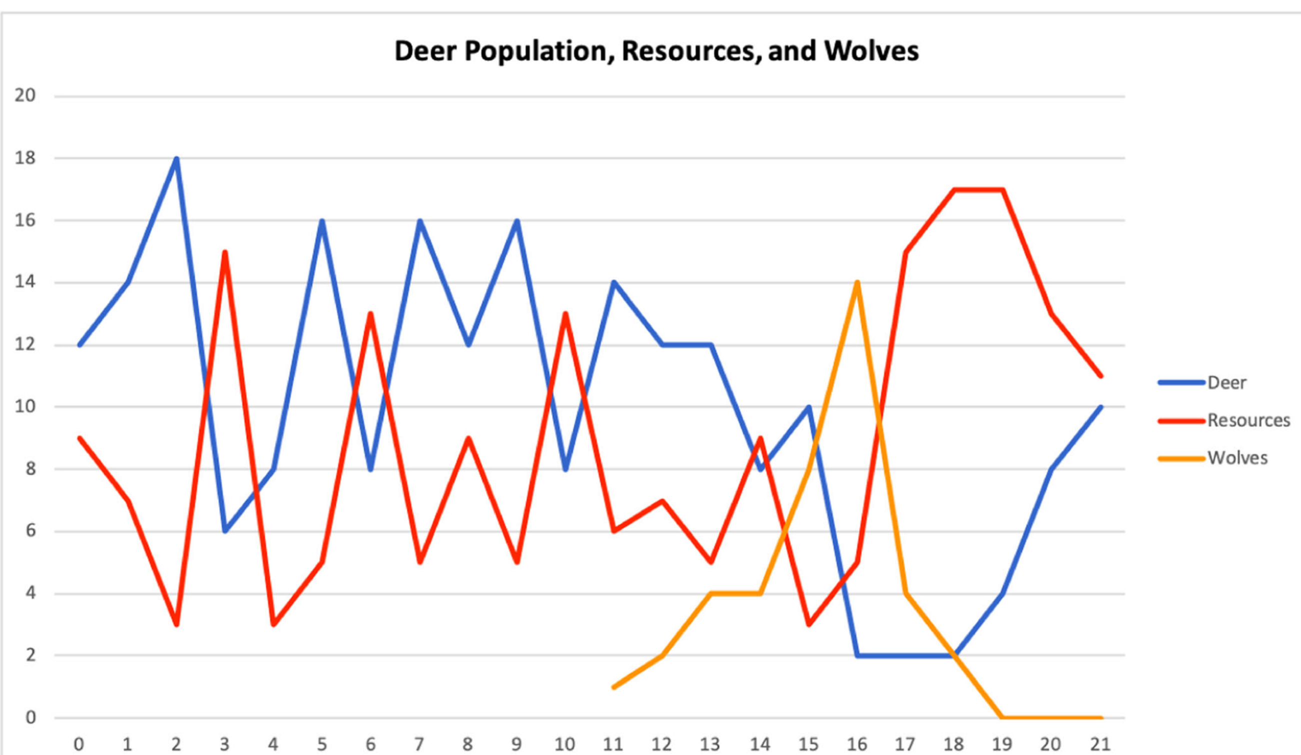

Fig. 7 Line graph generated with a spreadsheet program

they used in the *Oh Deer!* game. Simulations run using this model produce charts that demonstrate fluctuations in any number of deer and resources over 100 years, allowing students to see the effects of the population dynamics over longer periods of time. The model (Fig. 8) also provides an example to young students of how a computer can be used to simulate the game they physically acted out.

Building a complex model such as this was determined to be beyond the ability of the grade 3 students, and thus, in this instance, the teacher demonstrated the model and explained to students that it was built using the same rules that they used to play the game. We were curious how students would engage with a model that was purposefully built to mimic the very game they played. The simulated data it produce yielded results that were similar to what they experienced, but over a broader period of time and for larger populations. Here, students are exposed to the initial choice of whether a digital model of their game gives them better insight into studying the phenomenon, which helps them build capacity to think about when and how to design solutions to leverage computational power, another CT integration practice.

The spreadsheet model was constructed with a degree of randomness, which means that any time the spreadsheet is recalculated the model produces somewhat different results, thereby more closely reflecting the kinds of data variations found in the real world. By exploring different "runs" of the spreadsheet model, teachers can encourage students to abstract common relationships and patterns that emerge across different outcomes. Figure 9 illustrates two different runs of the simulation. While the particulars of the results look quite different, the same key patterns emerge—and mirror—some of the same relationships that students saw with their own data.

By working with the spreadsheet model that "followed the rules" of the *Oh Deer!* game, students were able to connect the simulated data with the data they collected and analyzed themselves. This connection allowed them to reinforce understanding of some patterns while exploring new patterns that were not possible given the limitations of the game. Here is an excerpt of a discussion from one class (Fig. 10) trying to make sense of the graphs in Fig. 9.

> Student A: In the other one [the graph of the data they collected], it kinda stayed in the same pattern. But in this one [the graph of the data from the spreadsheet model], it's making like a big circle shape, it almost looks like the letter D.

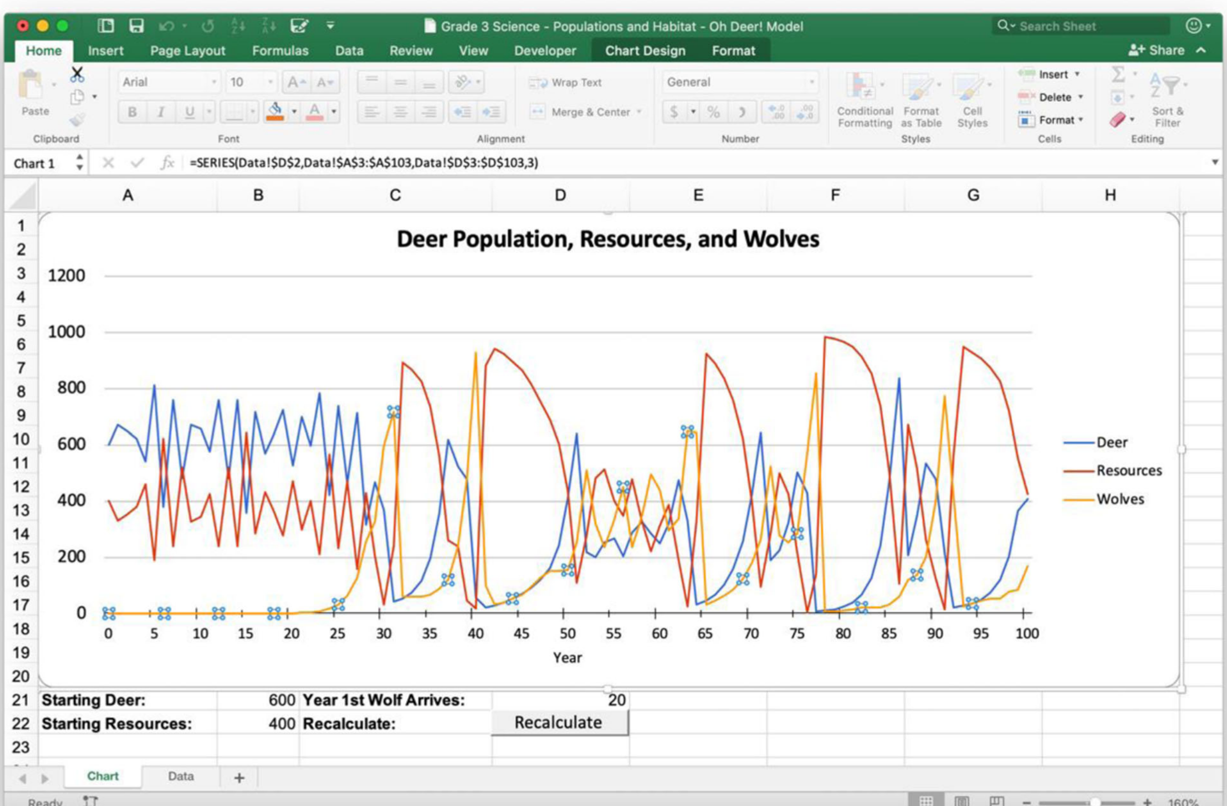

Fig. 8 The spreadsheet model

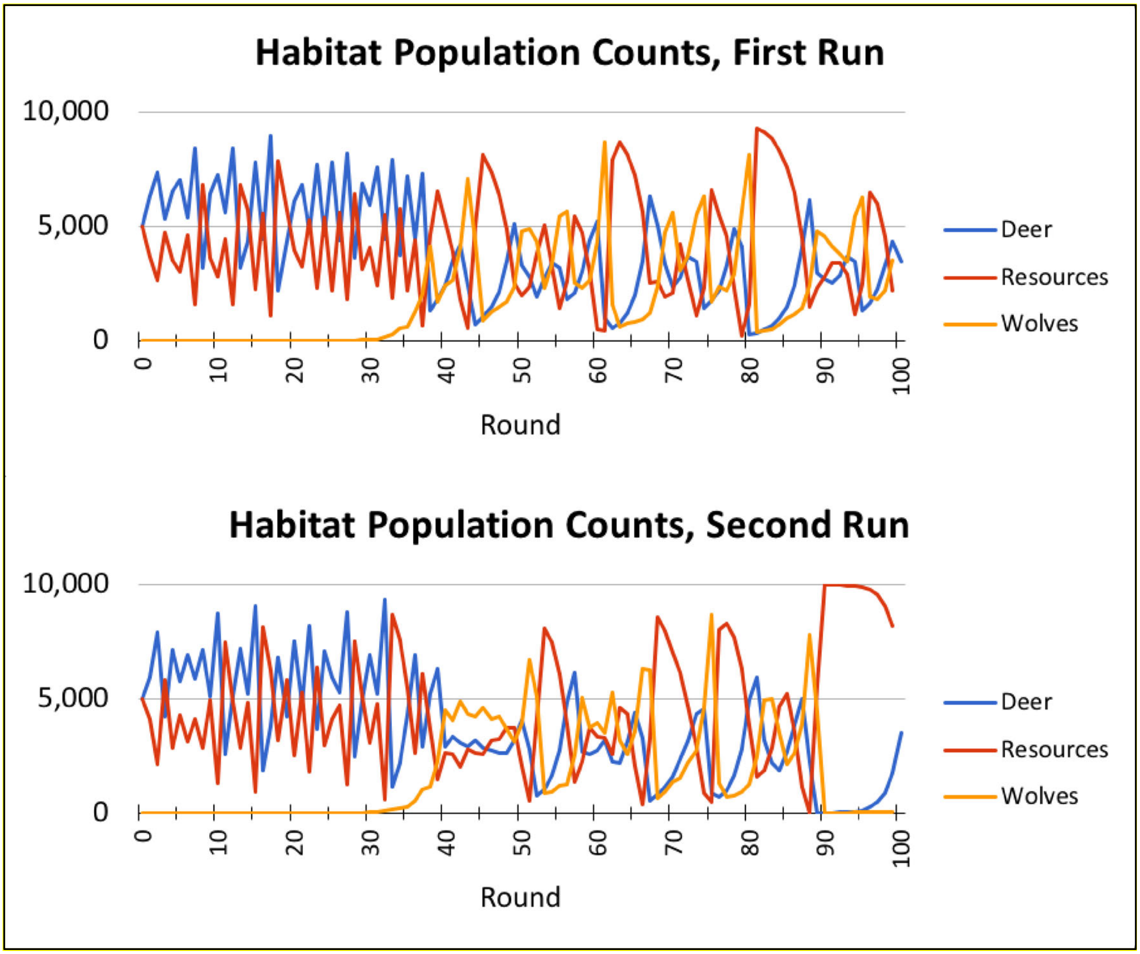

Fig. 9 Two runs of the spreadsheet simulation

Teacher: Why do the deer or wolf lines swoop up when they get low instead of spiking?
Student A: It swoops because it doesn't just go up right away, it takes some time.
Student B: It happens because once the wolves come in, there's only one of them. The next year there can't be 40 of them to make a spike.

Although students struggled to fully express why the graphs had these distinctive patterns, their comments suggest a basic understanding of why populations that have become extremely small could not rebound immediately. The explanation involves some understanding of both biology (how many offspring can be produced per season) and mathematics (how quickly a population can grow is bounded by how many animals are available to reproduce, an example of exponential growth absent mitigating factors). While these ideas are advanced for students in grade 3, discussions generated from examining the data, like the ones briefly described here, can provide a foundation for deeper understanding later on.

Discussion

The clear overlap between the three sets of standards (NGSS, CCSS-Math, and CSTA) suggests that, particularly in the early elementary grades, efforts to integrate CT into mathematics and science lessons may not be such a heavy lift. Not surprisingly, CSTA's standards are the most explicit in their call for the use of technology. So while many related disciplinary tasks involve data or modeling, what is different about engaging in these activities with a lens that specifically seeks to support CT—and what we directed our attention to as we enhanced and extended these activities—was the interaction with technology to perform the tasks, and to exploit (and explain) those opportunities technology affords that are difficult to attain without. Returning to our example, by extending the physical experience of the *Oh Deer!* activity by adding a role for technology in the lesson, students have access to a variety of ways to represent the data, a more extensive example of the patterns that can emerge from the model, and a richer understanding of the benefits (and potential perils) of relying on models and simulated data to represent and understand complex systems.

Fig. 10 Students describing what they see in the graph

One issue that we encountered in all the units we sought to develop was the challenge of developing *extend* activities that helped students explore science and mathematics with digital tools. We found that there was a lot of cognitive overhead for both teachers and students in engaging with technology, and that this overhead often made it difficult to use technology to enrich understanding of the content area. In this I-Mod, we chose to focus on integrating a spreadsheet program because it is perhaps the most pervasive data analysis tool used throughout industries today. It provides relatively simple tools to sort, summarize, and graphically represent data, and does so quickly, and can be used to create complex models. Most grade 3 teachers were familiar with spreadsheet programs, and several had already introduced one to their students, so the cognitive load for this integration was less than other attempts where the technology was more unfamiliar.

A particular outcome, which went beyond the scope of this project, was the potential for this activity to be used by older students. High school teachers, having seen presentations about this module and its outcomes, have expressed interest in adapting it for their programming classes. Students in higher grades could use the spreadsheet model to "look under the hood" and explore the underlying mechanics for themselves, manipulate the model to add additional features, or use it as a model to explore other phenomena.

Conclusions

Our efforts to integrate CT with core elementary content areas show promise. We observed students expressing ideas that demonstrated both CT and deeper science or mathematics understanding. Further, teachers have expressed interest in continuing their work. The majority of project participants reported that they were either already exploring additional opportunities to integrate CT into their lessons or planning to do so in the future.

By directly acknowledging those aspects of CT that were inherent in the *Oh Deer!* activity, teachers were comfortable engaging in the enhancements added to the unit, leading students in suggested discussions that connect and made CT concepts more explicit. Despite familiarity with spreadsheets in general, many teachers were initially hesitant to include the extension, but saw how the model afforded greater opportunity for sense-making around the population dynamics that were central to the unit.

This work has also raised new questions and challenges for us to continue to explore:

- It is an open question for us as to when, or even whether, teachers should be explicit in making students aware of CT, or whether highlighting the CT is more for teachers' benefit, helping to motivate them to engage their students in practices that serve both CT and disciplinary learning. We want students to learn to engage in the thinking, and not to memorize CT vocabulary (which we have seen some teachers have their students do).
- The lack of tested measures for both student and teacher CT understanding limit our current ability to rigorously investigate learning.

We encourage others interested in creating CT-integrated experiences for elementary students to explore these questions as well.

Acknowledgements The authors would like to thank other Broadening Participation team members for their expertise in bringing the I-Mods to fruition and their support during development of this paper: Irene Lee, David Reider, Anne Demallie, Joyce Malyn-Smith, E. Paul Goldenberg, Jeff Winokur, and Lydia Perry.

Funding Information The study was funded by the National Science Foundation (grant number 1543136).

Compliance with Ethical Standards

Conflict of Interest The authors individually declare that each has no conflict of interest.

Research Involving Human Participants All procedures performed in studies involving human participants were in accordance with the ethical standards as articulated in the 1979 Belmont Report and as reviewed by the Institutional Review Board at Education Development Center, Inc. (Registration No. 00000865). This research was determined to be exempt by the IRB under Section 101(b), paragraph 1.

Informed Consent Informed consent was obtained from all individual participants included in the study. Additional informed consent was obtained from all individual participants for whom identifying information is included in this article.

Disclaimer Any opinions, findings, conclusions, or recommendations reported here are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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