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Abstract

Learning Sciences researchers often design alongside the learners and other stakeholders they seek to support – involving them early and often in the conceptualization, development, and testing of learning environments (DiSalvo, 2016; Druin, 2002). This is done to preempt technical or pragmatic issues with design, to address problems of practice, and to build capacity for institutional change. However, designers often run into a more foundational issue: stakeholders hold different expectations about what types of learning a given design is meant to support (Könings et al., 2005; Könings e al., 2014; Wilkerson, 2017). These "interpretation(s) of innovation" (Fishman, 2014, p. 117) reveal different underlying goals and epistemologies held by designers, learners, and other stakeholders. In other words, they reveal which kinds of learning stakeholders expect or value, and whether those kinds of learning appear to be supported by the environment or not.

In this chapter, we argue that designers ought to (a) invite, attend to, and learn from different interpretations of designed innovations and (b) respond by expanding the designed environments to support more varied uses. We contend that this is especially needed when designed tools and environments are intended to introduce an audience to new or unfamiliar epistemic practices, such as those making use of digital tools.

Then, we describe two methodological approaches we have developed to engage in this type of collaborative design. The first, *longitudinal tool interviews*, involves conducting repeated task-based design interviews with learners over extended periods of time. These interviews invite active negotiation of what kinds of learning a digital tool should to support. The second, *backward conjecture mapping*, engages stakeholders from diverse educational contexts with the same digital tool, in an effort to support a variety of applications. Both approaches provide opportunities for researchers to renegotiate their understanding of tool design, for learners and educators to experience new epistemological orientations and knowledge-building strategies, and for both parties to expand their conceptualizations of what is possible when digital tools and practices are introduced into formal learning environments.

9

LEARNING FROM “INTERPRETATIONS OF INNOVATION” IN THE CODESIGN OF DIGITAL TOOLS

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Interpretations of Innovation and Expansive Design

In UC Berkeley’s Computational Representations in Education (CoRE) research group, we explore how students and classroom communities develop digitally mediated ways of building knowledge in scientific disciplines. Simulations, data analysis tools, and discipline-specific programming languages have become part and parcel of what it means to do science. Educators and researchers have also extolled the pedagogical benefits of scientific technologies for learning, and digitally mediated practices have made their way into standards and curricula (e.g., NGSS, 2013; CCSSO, 2010).

However, there are a number of reasons why integrating digitally mediated scientific practices into classroom environments is especially complex. Exclusionary digital cultures limit who and what is valued in STEM disciplinary communities, both on a societal and classroom level (Vakil, 2018). And although digital tools are pervasive, their epistemic status is unclear even within professional knowledge communities (Greca et al., 2014). It is also unreasonable to expect that simply adding digital tools to a classroom will *de facto* introduce new corresponding practices such as data analysis or simulation-based reasoning. Practices are not simply the transfer of established disciplinary routines to educational contexts, rather they emerge and are adapted through negotiation in response to a community's needs (Lehrer & Schauble, 2006).

It is unsurprising, then, that learners may not accept that building a computer simulation of a garden or visualizing a dataset are reasonable ways to construct knowledge about their surrounding worlds. It is also unsurprising that in a codesign setting, learners and other stakeholders may envision new functions for digital tools – including support practices and forms of learning that the designers have not anticipated. We have observed this repeatedly in our own work. Students have rightfully rejected tools that do not align with their own productive modes of reasoning (Gravel & Wilkerson, 2017; Wilkerson et al., 2018). Teachers have deftly repurposed digital tools designed for scientific modeling to instead support socioemotional and communicative development (Wilkerson et al., 2016). Ignoring such interpretations of innovation can restrict the utility of the designed tool and devalues stakeholders' insights into the activities that we, as participatory design-based researchers, claim they know best.

We have been developing methods to invite, attend to, and make meaning of the epistemological plurality that is often hidden within such interpretations of innovation. This is part of a growing variety of efforts within the fields of the Learning Sciences and Human-Computer Interaction (see DiSalvo et al., 2016; Gomez et al., 2018 for recent reviews). Like these colleagues, we are interested in involving students, teachers, and other stakeholders in the design of tools early and meaningfully. We draw methods and approaches specifically from Druin and colleagues' conceptualization of children as design informants (Guha et al., 2013), and, like Könings and colleagues (2014), we focus on relationship building to allow for design feedback that may reveal tensions between our own goals and expertise and those of other educational stakeholders.

At the same time, we are also interested in explicitly attending to, and disrupting, the epistemologically and socially problematic ways in which we as researchers and curriculum developers privilege digital tools and technocentric approaches in school and scientific settings. Toward this end, we recognize how entire learning ecologies and communities can play a role in reorganizing how power and epistemology operate within a learning environment. Scholars such as Bang, Vossoughi, Gutiérrez and others (Bang & Vossoughi, 2016; Gutiérrez & Vossoughi, 2010) have engaged in social design that explicitly seeks to interrupt and reimagine how power and epistemology operate within learning environments.

Bringing these approaches to design together motivates us to consider how digital tools, as a design artifact, may intersect with configurations and reconfigurations of power and epistemology within learning environments. Thus, as a result of reframing as we listen to users (Schon, 1983), our goals as designers of digital tools expand to include how those tools might contribute to a variety of dynamic already-existing and still-to-be-imagined spaces and practices. Though our focus is on the design of the tool, our vision of its position within different activity structures is collaboratively shaped with the stakeholders we consult.

In the remainder of this chapter, we review two approaches that we have found particularly useful for inviting and supporting multiple interpretations of digital tools. For each, we describe the method and explore how it encourages designers to evaluate: What is our goal for this design? What is the learners' goal for this design? And, how does this methodology allow us to envision an expansive design that supports both?

Longitudinal Tool Interviews

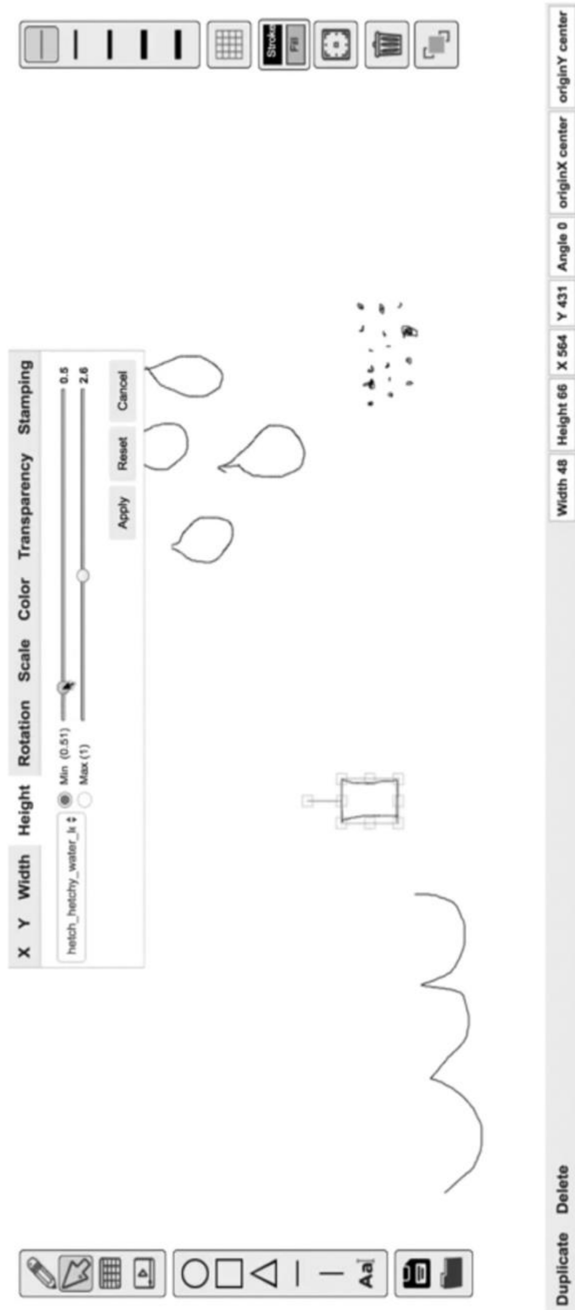
Longitudinal tool interviews are series of task-based, semi-structured collaborative design interviews conducted with individuals or pairs, over several months to a year. During this time, we engage participants repeatedly with a prototype or early version of a digital tool through a shifting combination of directed, open-ended, and design tasks. These include: (1) using established tools and activities to familiarize participants with the epistemic practice we seek to support; (2) introducing the tool prototype through video demonstrations, live tutorials, or a structured activity; (3) providing semi-structured tasks that engage participants with the tool in ways aligned with intended epistemic practices; (4) allowing open-ended exploration of the tool to explore other applications; (5) asking participants to propose and pursue their explorations with the tool; and (6) periodically inviting participants to suggest classroom uses and modifications throughout the process.

At their core, longitudinal tool interviews are meant to provoke negotiation between participants and researchers about *what functions the tool is expected to serve*. Components (1) to (3) introduce the designer-intended epistemic functions of the tools, which are often new to participants.

Components (4) to (6) invite counterproposals for other functions the tools could serve. Throughout the process, the researcher clarifies different "interpretations of innovation" that arise, allowing for an active negotiation of the roles of the tool in participants' knowledge-building, which allows for the investigation of students learning about new epistemic practices, as well as the expansion of the tool's design. We describe one example of longitudinal tool interviews in the next section; we have also employed this approach in other studies (e.g., Wilkerson, Lanouette, Shareff, Bulalacao, Under Review).

An Example: DataSketch

DataSketch is a tablet-based, programmable ink sketchpad designed to support middle school students in visual analysis of time-series data (Figure 9.1). It allows learners to link visual features of their own drawings (such as a particular object's height, color, position, orientation, or opacity) to time-series data. As their visualization is "played," the drawings animate to reflect changes in the dataset over time. DataSketch was originally conceived to be a digital tool to support *exploratory data visualization* as an epistemic practice, highlighting the construction and use of data visualizations as a way to engage in statistical exploration and hypothesis building about natural and social systems (Fox & Hendler, 2011).



ALT TEXT: An image showing 4 drawings including a wavy line, a rectangle, 4 water drops and a group of small dots. There are two vertical menus on the left and right side of the screen with drawing tools such as shapes, colors, line thickness, save and delete. At the top there is a horizontal menu with two scales for choosing the minimum and maximum values for the height of the rectangle.

Figure 9.1 DataSketch was initially designed to support exploratory data visualization; learners also perceive it as useful for communicating the implications of patterns in data.

Throughout the early stages of development of the DataSketch tool, we engaged middle-grade participants in a three-part longitudinal tool interview sequence with DataSketch, conducted over a period of several months. A total of nine students in grades 5 through 8, drawn from two suburbs of the San Francisco Bay area of California, participated in the full interview series. Participants were between 10 and 14 years old, attended both public and private schools, and interviews lasted between 45 and 90 minutes. We recruited participants through a network of colleagues and via public posting in online local community networks.

During the first interview, participants explored several interactive visualizations produced by national news outlets and public agencies (e.g., the New York Times, the United States Geological Survey) about current events including climate patterns, economics, and a recent drought in the US state of California. We also asked learners what other topics they believed would be productive to explore using interactive visualization. During the second interview, students were again provided with an interactive visualization, this time about recent local weather. We then introduced students to the DataSketch tool with a tutorial video and invited them to construct their own visualization of the same local weather data. We then allowed for a period of open exploration with the tool and discussed potential explorations and applications of DataSketch both within and beyond the context of school science. The final interview included two design tasks with an updated version of DataSketch with several new features suggested by participants during the second round of interviews.

Learners' Interpretations of DataSketch

Over the course of the interviews, learners identified possible uses of DataSketch that we had not initially intended but have significant pedagogical potential. These include illustrating patterns in data using animated representations common in school (such as line graphs or bar charts); visually communicating contextual interpretations and implications of data; and precisely communicating changes in a specific parameter as it varies over time. For example, Carol was an 11-year-old public-school student whose family engaged in hobbyist data exploration. She was comfortable experimenting with the software from the beginning and articulated a number of distinct interpretations of innovation that reflected patterns we identified more broadly across our dataset.

From the beginning of our interview series, Carol clearly understood exploratory data visualization as an epistemic practice we sought to support. This was evident in how she approached the structured tasks involving interactive data visualizations, and how she leveraged the DataSketch tool. Throughout the series of interviews, Carol offered a number of suggestions on ways to improve this digital tool so that relationships among variables in datasets could be more systematically identified and explored. During an early session, she noted that the animations DataSketch generated were too fast to make good sense of the data and recommended controls so users could set a speed for the visualization and pause it to more closely inspect specific points of interest. Later, she proposed a feature to better connect specific moments in the dataset's time progression to specific data configurations.

Other interpretations emerged, however, when we prompted Carol to discuss other ways she might expect to use DataSketch. With respect to the classroom context, she described data visualization as a way to demonstrate mathematical competencies to teachers, stating "If I was doing it [*creating a visualization with DataSketch*] for a school project, I would probably take a little bit more time to draw everything. Because I'd be getting graded on it, so I'd want a good grade." This particular feedback about performance expectations was common, as students made clear they would understand the tool to be more serious, valuable, and reflective of authentic scientific exploration if the products generated were aesthetically appealing.

We also observed Carol interact with the software and make suggestions that helped us better understand what constituted deeper learning about exploratory data visualization as a target practice. For example, after creating an early visualization about local weather patterns, Carol commented that she was getting distracted when there were too many things moving on the screen: "Um, I kind of feel it was pretty distracting for me. I kept looking at the cloud getting big and small and big and small, so I'm not sure that was probably the best way to show it." These comments imply that Carol was considering how her choice of specific animation actions (changes in width) might have impacted her ability to notice and follow patterns in data. Throughout our data, we observed participants commenting on and revising visual selections to better facilitate comparison between values – that is, to better accomplish the sort of exploratory analysis we sought to support.

Expansive Design Revisions to DataSketch

Many of the suggestions which led to revisions of the DataSketch tool were first proposed by students while they engaged in components (1) to (3) of the longitudinal tool interviews. Because of these, these suggestions were related to our own target epistemic practices as design goals. For example, we both (1) reduced the speed of the animation and (2) introduced an optional grid for positioning objects to assist students in comparing patterns in data as they are represented within the visualization (e.g., two clouds showing humidity in two different cities). Other redesigns of DataSketch emerged as students participated in components (4) to (6) of the longitudinal tool interviews. For example, we followed advice from students to (1) expand drawing resources to include ready-made shapes, (2) provide a greater variety in styling options (e.g., filling in shapes with color), and (3) reorder the appearance of overlapping components of a drawing. These changes were proposed by students as they more freely engaged with DataSketch and reflected on its potential as a tool they might use in their home or classroom contexts (where it might be used for communication and demonstration of skill, not just exploratory analysis).

Some of the suggestions that students made during the more open-ended components (4) to (6) of the interviews, though emergent from their desires to create more aesthetic visualizations that clearly communicated patterns, very clearly served *both* students' purposes and our intended purposes of data exploration. For example, students asked for the ability to define the center of rotation for a shape, which permitted them to create more visually interesting animations and to support the creation of epistemically productive visualizations for discovery, such as the Nightingale rose (Brasseur, 2005). They also asked for the addition and animation of text and a chance to preview the behavior of each component of their sketch so they could consider them independently before observing the full visualization.

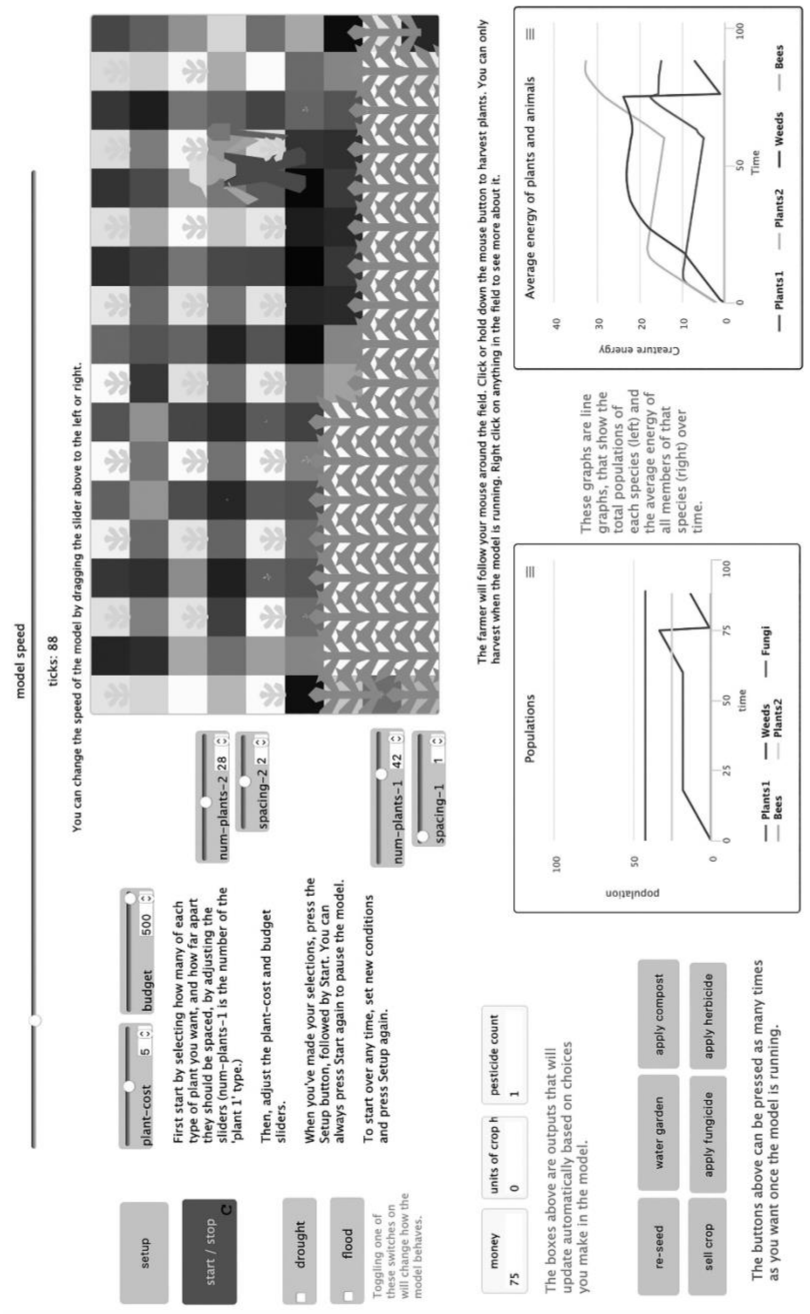
Backwards Conjecture Mapping

Conjecture maps, introduced in Sandoval (2014), allow researchers to specify the underlying theories, anticipated behaviors, and intended outcomes that motivate the design of a given tool or learning environment. In a conjecture map, designers articulate the broad *Conjecture* that drove the design, the *Embodiment* of that conjecture through socio-material design elements, the *Mediating Processes* or mechanisms by which those design elements are anticipated to contribute to learning, and the intended learning *Outcomes* of the design. Backward conjecture mapping complements this focus on designer intention by offering a correspondingly detailed analysis of the different ways an environment is perceived and taken up by teachers and students. As with longitudinal tool-based interviews, we engage participants first in task-based activities with the tool; then invite open-ended exploration of some phenomenon of interest and ask participants about whether and how they may use it across a variety of contexts in which they find themselves (e.g., across school subjects, within classroom or after-school environments; for a lesson versus for self-guided inquiry).

Next, we analyze interviews "backwards" through the conjecture map, with the assumption that if participants suggest a new *Learning Outcome* that is possible with the tool, this means they can see some elements – some *Mediating Processes* and *Embodiments* – already present within the tool's design that may support that use and imagine others who might further support it. We often begin by identifying the learning outcomes suggested by participants during interviews, adding any that we may not have originally intended to the conjecture map. We might also identify emergent interpretations of the tool through new mediating processes or design embodiments proposed by participants. Then, for each intended or proposed learning outcome, we attend to participants' actions and suggestions for the tool to trace their envisioned connections through embodiments and mediating processes that would contribute to their intended goals.

An Example: GardenSim

GardenSim (Shareff, 2018) is a modeling toolkit designed within the NetLogo programming environment, comprising two modes of interaction. First, learners can interact with a "sandbox"-style visuospatial simulation that allows them to perform "actions" such as planting seeds, adding compost, removing weeds, and more within a virtual plot, while accessing graphs and numerical analytics that report the state of the plot (Figure 9.2).



A composite of five images. It includes a garden image with a farmer in the top right corner, and two line graphs in the bottom right corner. The first graph shows the population of two types of plants, weeds, fungi and bees over time. The second graph shows the average energy of two types of plants, weeds, and bees over time. The left part of the image includes instructions on how to use the model garden, buttons to start or stop the model, add drought or flood conditions, perform agricultural actions such as applying compost, and six slide bars for choosing the cost of a plant, the number and spacing of two types of plants and the budget available.

Figure 9.2 GardenSim was designed to support computational modeling in ecology through visual simulation.

Second, learners can access and modify the simulation's underlying code in order to adapt the space, add new components (e.g., pollinators, watering), and so on (Figure 9.3). GardenSim was designed to support computational model-based exploration and theory building about ecological relationships. Specifically, we hoped that the environment would provide learners with a "test bed" to model and explore relationships and potential actions they might observe or perform in their own garden spaces.

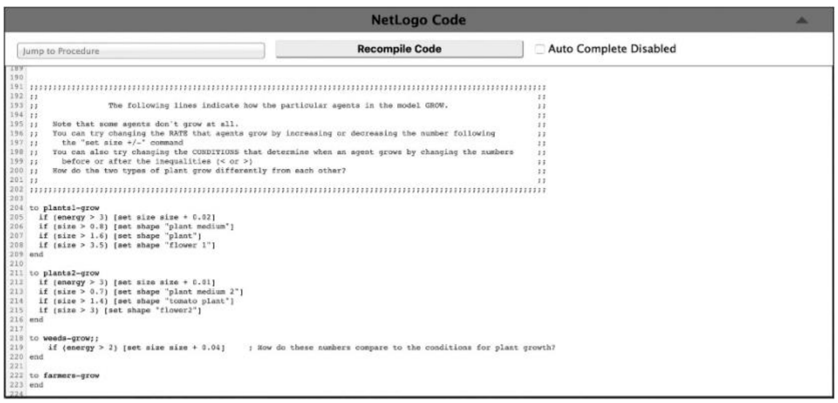
Four middle school students and four of their teachers were interviewed as they interacted with an early prototype of GardenSim. All were drawn from a school site with an active student garden, where Shareff (second author) was working to develop garden-based activities across the academic curriculum. Participating students and teachers were intentionally selected to reflect a diversity of grades (6–8), experience levels with simulations, and academic subjects (Math, Science, English/Language Arts) within the school. Participants explored the garden model while talking aloud about what they were seeing and doing, and their speech and actions on the screen were recorded and synchronized.

Teachers' and Students' Interpretations of GardenSim

A backwards conjecture mapping analysis of all eight interviews revealed a number of new and revised potential learning outcomes GardenSim might support. These included learning specific mathematical content, exploring cause and effect, and learning about food systems. There were also three emergent mediating processes that participants identified to be well-suited to support those learning outcomes – finding mathematical relationships within the model, iterating on past experiences to change outcomes within the simulation, and evaluating simulation design and accessibility. At times, the maps that emerged were quite complex as participants discussed multiple possible outcomes at once. For example, one participant proposed that students could improve the resemblance of the simulation to their actual school garden, noting that this would support both connecting to garden experiences and developing design and computational thinking competencies.

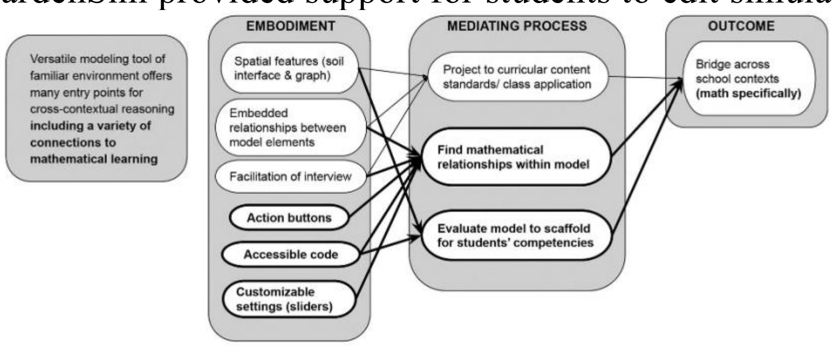
To demonstrate how backwards conjecture mapping informed specific design revisions in more detail, we focus here on one emergent outcome:

Learning specific mathematical content (including linear relationships, rates and ratios, and negative numbers). When the environment had been originally designed to support garden connections across the curriculum, it was anticipated that mathematical connections would be made primarily through the graphs. However, it became clear in several interviews that both teachers and students saw the potential for more expansive connections to topics in mathematics including linear relationships, rates and ratios, and negative numbers. Figure 9.4 demonstrates our initial conjectured supports for cross-curricular connections (plain text) and the elaborated connections and improved supports (bold) for specific mathematical learning outcomes that emerged from the interviews.



ALT TEXT: An image showing netlogo code that includes commands for growing two types of plants and weeds.

Figure 9.3 GardenSim provided support for students to edit simulation code.



ALT TEXT: Three round rectangles each titled Embodiment, Mediating process and Outcome. The Embodiment rectangles includes six subcategories, three of which are bolded. The mediating process rectangle includes three subcategories, two of which are bolded. The Outcome rectangle includes one subcategory.

Figure 9.4 Bridging across school contexts was an intended outcome for GardenSim; but supporting particular mathematics content emerged as a more specific goal for several participants. This partial conjecture map highlights in

bold the additions to GardenSim's design and underlying theory that emerged from interviews.

For example, one sixth grader who had school-based garden experience noted that a curricular connection they found in the simulation tool was to "Math because you can actually play with, ok so you can be like, um 'I'm gonna sell this for this huge full-grown plant for 50 dollars' so they can get more out of it." Here, we inferred that the student was prompted to consider mathematical relationships through the action buttons for pricing and selling crops and the embedded relationships between plant size and harvest yield. Other student interactions reinforced the idea that the simulation could support learning of more specific mathematical concepts. One eighth grader noted that "there's this [*graph*] and I think there's some sort of population that is growing up, which is probably this [*plot of weed population*] and something that is staying the same [*plot of plant population*]," suggesting that the graphs prompted reasoning about relative rate of change.

Teachers also elaborated a number of specific mathematical connections they envisioned could be better supported using the simulation. One science teacher, while interacting with the code, said

> It'd be interesting when the students start inserting code, maybe if they had some, 'well I heard somewhere the relationship between nutrients in the soil and plants is a linear equation, and I have an idea of the equation,' and to have a snippet of code that they could put in. Because I'm guessing for them like, well two things. For them to come up with the code, themselves, for something that complex would be difficult so to have snippets that they could drop in would be helpful.

This teacher's recommendations reflected an interest in both mathematics learning and editing computer code as learning outcomes of the simulation environment and made concrete recommendations of design features (code snippets) that could support these dual goals by identifying mathematical relationship types and providing scaffolding for engaging with programming aspects of the tool.

Expansive Design Revisions to GardenSim

In response to these interpretations of innovation by students and teachers, GardenSim was updated with several new features intended to amplify opportunities for mathematical learning. To facilitate finding mathematical relationships within the model, we developed a second plant breed with different growth and nutrient consumption rates, more action buttons (water, fungicide) that cost money and are variably available based on the model condition (drought or flood), and versions with varying plots. One model has histograms that display the nutrient and hydration distributions of the soil, while another has a line graph of the average energy of all creatures in the ecosystem, offering different insights into the mathematical relationships of biotic and abiotic model components. To scaffold students' engagement with mathematics in the code, text comments were added that suggest exploration of the numerical relationships between model elements, and demo videos used in a classroom study showed students how to generate average values and counts from the "observer" toolbar.

The example given here focused on learning specific mathematical content as being only one of many findings from our codesign sessions, though this finding was particularly strong across both teacher and student participants. Other findings included, for example, supporting connections between different school subjects (mathematics, science, writing, business) and across contexts including home and agriculture, even though the environment was originally designed specifically for science classrooms and connecting the classroom and garden, respectively. This demonstrates how not only the goal of tool design is expanded, but also the contexts in which the tool might be useful.

Discussion

We have found both longitudinal interviews and backwards conjecture mapping to be productive approaches to designing digital tools that carry with them new and unfamiliar epistemic practices. Both approaches involve making explicit – both to ourselves in the design of interviews and conjecture maps and to participants – not only the intended *use* of the tool itself, but also the underlying *epistemic goals* and *social configurations* we seek to support. While we have observed these epistemic and social expansions using both methodologies, we anticipate that the longitudinal tool interviews are well-suited for reenvisioning computational practices, whereas backwards conjecture mapping is well-suited for envisioning new or different learning environments and social organizations in which tools might be used. Making the epistemological dimensions of interventions, especially interventions that involve representational tools, explicit is an important component of scientific "meta-knowledge" still underemphasized in science education (White et al., 2011). These approaches also both involve making space for the contributions and alternative interpretations of innovations by learners and educators very explicit. They offer clear structures both within the data collection processes and during later analysis how we might distinguish, compare, and negotiate alternative interpretations, with implications for both design and theory building.

More importantly for us, we find that these approaches to codesign keep us more accountable as researchers and designers. Asking students and teachers explicitly about what a tool might be good for (or not!) shifts blame away from our intended audience when they may not use a tool as intended, instead encouraging us to ask how we might create a tool that is worth their time to learn and use. These approaches to codesign also expand both the object of design – from the software tool itself to the purposes and environments for which it may be adapted – and the focus of research, as emergent themes from collaborative design sessions suggest new areas of theoretical and empirical exploration in future iterative work. In this way, codesigners become codesigners of not only tools, but also new imagined ways of learning and becoming in computational science.

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