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Computational Tinkering in Science: Designing space for computational participation in high school biology

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Computational tools are being integrated into science classrooms, but in ways that are often procedurally prescribed, constraining learner agency and ignoring student purposes and epistemic practices. We draw on theory and approaches from making-oriented education to introduce *computational tinkering in science* as a construct for thinking about and designing for learning with computational tools. Across two design research cycles in high school science classrooms, we analyze episodes of student activity to understand how practices of computational tinkering might translate from informal settings to formal science classrooms to enable learners to engage in practices that reflect authentic scientific work, draw upon learner experiences, and support more equitable participation in science. Looking across both student-centered and curricula-centered science classrooms for *emergent goals*, *rapid iteration*, and *noticing and reflection*, we saw computational tinkering take shape during moments of *play*, *troubleshooting and tuning*, and *sharing*. We discuss findings and implications for practice in relation to professional science practice and goals of science education in an era of computational ascendancy.

Keywords: computational thinking, tinkering, biology, epistemic agency

Increasingly, computational approaches to scientific investigation are being integrated into science education to better reflect contemporary scientific practice. These efforts often take up definitions of *computational thinking* that pose a set of practices derived from computer science: algorithmic thinking, debugging, problem decomposition, and the like (Wing, 2006). Others have highlighted computational practices in particular problem contexts, like building computational models or investigating complex systems (Weintrop et al., 2016). While these definitions articulate important computing concepts, practices and skills, narrowing instruction around them may be in tension with science education reform efforts to foreground student agency and reasoning practices, and to connect work in the classroom to learners' identities, experiences and concerns that extend across settings.

To align the integration of computational tools with these goals, we need to consider how computational tools are adopted or adapted by learners for existing goals and activities, and how their use reciprocally shapes participation in scientific practice. We look to theories of interaction with computational systems that posit computational tools not simply as tools for automating solutions to problems, but also as a medium for connecting to people, performing identity work, or participating in communities of practice and place (Guzdial, et al., 2019; Kafai & Burke, 2014, Sengupta et al., 2018). These perspectives emphasize computational tools as "objects to think with" (Papert, 1980), engaged with through construction, sharing, repurposing, and transformation, as well as appropriation. We see a need for conceptions of computational thinking to include consideration of the whole human and technical computational systems and to include *experiences* of using computation tools: grappling with uncertainty, making judgments, and trying to do something within a particular moment and social or disciplinary context (Sengupta, et al., 2018).

As an alternative or addition to *computational thinking*, we use the construct of *computational tinkering* to highlight that understandings of computational systems and how to use them arise from materially- and socially- situated activity in which practices, goals and tool emerge and co-evolve (Hardy, Dixon, & Hsi, 2020). Within primarily informal educational settings, computational tinkering has been used to support opportunities to learn about coding and electronics, while at the same time foster creativity, connection, personal expression, and a resourceful, student-centered approach (Berland, 2016; Kafai & Burke, 2014). Noting similarities between accounts of making and tinkering as knowledge-building and inquiry, and accounts of professional science practice that highlight the centrality of instrumentation and human intervention (Pickering, 1995), we expand on the idea of computational tinkering and pose it as a valuable pedagogical design strategy for the integration of computational tools into science classrooms. Here we present cases of computational tinkering drawn from two iterations of design research in high school biology.

Background & theoretical framework

Making- and tinkering-oriented learning environments have the potential to benefit identity work, adaptive problem solving, and equity in learning, supporting access to repertoires of practice, collaboration with peers as mentors and valued contributors, inclusion of personal and community concerns, and learning through iterative engagement (Vossoughi, et al., 2016; Martin, et al., 2018). Central to tinkering in learning is *bricolage* - making use of whatever materials and strategies are at hand, and allowing available resources to shape and inform goals (Papert, 1980). As a style of activity, bricolage stands in contrast to a more top-down, analytic approach in which goals are set in advance (Turkle & Papert, 1990). In tinkering, goals co-evolve alongside objects and understandings, with emergent, small-scale objectives arising along a pathway toward longer term goals. While bricolage may contrast with (or compliment) more planful approaches, it is nonetheless a way of directly interacting with and understanding the world, a "sound way to gain expertise with complex technical content" (Berland, 2016; see also Resnick & Rosenbaum, 2013). Understanding bricolage not merely as a novice practice or early stage of development, but as an expert way of working, is central to a case for tinkering as a support for epistemic agency and epistemological pluralism: a valuing of and respect for multiple ways of learning and knowing that can reduce barriers to participation in STEM learning (Turkle & Papert, 1990). Through tinkering, learning becomes powerful not as it ascends away from the specific, but as people find ways to do things in more moments and for more personal purposes.

From tinkering to *computational* tinkering

Engagement in computational tinkering has been described most often in informal educational settings including museums, science centers, and after school programs, with technologies and fairly open-ended tasks oriented toward aesthetic expression or playful exploration with low-tech materials. The most common use of the term computational tinkering could be termed "a playful approach to building with code" (Wilkinson et al., 2017) and describes efforts that draw from constructionism (Papert, 1980) to enhance teaching of coding and/or computational thinking practices with practices and characteristics of making and tinkering. This use highlights aspects of tinkering like play, idea generation, creativity, remixing, collaboration, and iteration; and theories of constructionism (Ryoo, 2016). This poses computational tinkering as a pedagogy that allows learners to access existing expertise and interest, and act as "producers" directing their work toward individual or community purposes. Second, engagement in computational tinkering has been posed as an imperative to help young people develop critical thinking and stances necessary to not just create with digital technologies, but to be able to critique them (Ryoo, 2016; Miller & Horneff, 2017). Echoing ideas of partnerships or relationships with technologies, these perspectives see tinkering as important to demystifying computational technologies and dispelling fear (Presicce, 2017). Last, others frame computational tinkering as a valued way of thinking, acting, and creating knowledge in its own right (Resnick & Rosenbaum, 2013). More than relying on tinkering as pedagogically expedient, these perspectives take more seriously Papert's original use of "computational thinking" as a way of producing knowledge – a way of creating new knowledge, new pathways, and new possibilities – rather than a way of discovering those that already exist.

Building on these strands, computational tinkering is cast as a way of reaching new audiences, elevating perspectives not already a part of mainstream STEM education, and bringing a measure of equity to computing education. This builds on a longer history of work with e-textiles and tangible computing that has brought together divergent disciplines (like art and science) through development and use of novel computational tools, and that has worked both to bring a wider range of people into computing fields and to widen the range of what a computational community can mean and do (see Kafai et al., 2014). This echoes voices in a larger "maker" education community that see opportunities for (though also threats to) addressing inequities in education by grounding work in learners experiences, relationships, and epistemic resources (Vossoughi et al., 2016).

Computational tinkering as an approach to supporting science learning

Drawing together accounts of creative computational tinkering with those of professional scientific practice, we consider computational tinkering to be both a material and epistemic practice. Instrumentation and measurement technologies are central to both naturalistic and experimental scientific work. Scientific practice is characterized by an iterative, back-and-forth "mangling" of instruments, concepts, and practices (Pickering, 1995), and modern practice in particular involves working with, developing understandings of, and manipulating or modifying computational systems that are distributed across digital, physical and human elements. Taking this view, the scientist's relationship to materials, concepts and technologies parallels that of the tinkerer (Brown et al., 1989).

We highlight three aspects of computational tinkering that both make it authentic to scientific practice, and distinguish it from the abstract or analytical "thought processes" common in views of computational thinking (Wing, 2006): (1) **emergent goals** and their co-evolution with resources and understandings; (2) **rapid iteration** as a movement back and forth between materials, computational tools, and understandings of target behavior or phenomena; (3) **noticing & reflecting**, through verbalized observations and decisions, as well as tacitly through response to unexpected results. Through this lens, the activity of computational tinkering provides a context in which learners can engage in identity work that legitimizes a wider range of ways of knowing, doing and being. Our research questions are (1) What forms does computational tinkering take when designed into formal science learning environments? (2) What opportunities does computational tinkering present for concurrent identity work and engagement in scientific practice?

Research context & methods

This study took place in the context of a larger research study of integrating computational thinking practices into high school biology using a toolset of open-source software and low-cost sensors to interface with the sensor and data (Hardy, et al., 2019), and worked with teachers to create a roughly two-week long unit on photosynthesis and cellular respiration that could be used in the context of 9th grade environmental science or 10th grade biology. Teachers attended a multi-day summer workshop to learn about the curricular activities and sensor/actuator kit before introducing these with students during the school year. Round 1 of the study took place in an urban, tuition-free public charter school. Of its students, 83% qualify for Free or Reduced Price lunch, 78% are English Language Learners, and 90% of graduates would be the first in their families to go to college. Three classes of 9th grade Integrated Science students participated in the study. In Round 2, we expanded the study to include four new teachers across three public high schools. These high schools included two suburban high schools, one of which serves 49.4% economically disadvantaged students, one which serves 2% economically disadvantaged students, and an urban high school that serves a racial diversity of students (33% African American, 39% Hispanic American, 16% Asian American, 7% White, and other races).

Designed to make visible more computational components than commercial sensors, the kit used by teachers and students included CO_2, light, temperature, humidity, and oxygen sensors, as well as a relay that students could use to turn a lamp or fan on/off through the programming interface. Activities across the unit had the students use the sensor kits to measure conditions (CO_2 and light, primarily) inside a closed container containing spinach leaves undergoing photosynthesis and respiration, as well as CO_2 levels in ambient air and in human breath when resting and exercising. After some initial prototyping and refinement of the technological tools and activities, we designed an introductory day with the sensor kit and software as a time for "sensing & responding" in which students could engage with the kit through open-ended prompts and with room to troubleshoot, tinker and try new things as they figured out how it worked. In Round 1, as participant observers in support of a lead teacher, we implemented the tinkering activities as part of a two-week long unit with three classes of 9th and 10th grade environmental science.

In the second round with the four additional teachers, there was a range of teaching styles, levels of experience with teaching with technology, and a wide range of high school students. To fit curricular goals and teaching styles of these classrooms, as well as to push further our understanding of how computational tinkering might fit into core components of formal science curricula, we shortened the initial tinkering time, but designed two activities that we believed would allow for kinds of computational tinkering authentic to scientific practice. We describe these activities in more detail below in our presentation of results.

Data production & analysis

During the classroom implementations, researchers in the classroom acted as participant-observers, answering questions from students when sensor kits did not seem to be working, talking before and after class with teachers about goals, strategies and how things went. In each of 16 classes across the four schools (Rounds 1 and 2), at least two focal groups were selected from consented students from each class for close observation and video recording. Researchers took field notes of overall classroom activity and recorded video of focal groups of consented students, as well as photographs or photocopies of student work. Before lab activities, students took background surveys about their experiences with and interest in science and technology. After the first classroom implementation, we conducted semi-structured interviews, lasting 20-45 minutes, with 18 students. The interview protocol focused on the students' projects and experiences, and included prompts about what the students did and how they felt in class, for instance about what they felt like they were trying to do during a particular activity, or times when they felt surprised or frustrated.

To answer our research questions, we began by reviewing data from the initial, introductory sessions of Round 1, as well as subsequent work in the unit. We reviewed field notes and video from focal groups, looking for moments that displayed aspects of computational tinkering highlighted above, as well as for moments that were creative, playful, or in which students seemed to express some aspect of identity (Engle et al. 2007). We also made use of interview analysis conducted for another part of the study to identify orientations and interests that helped us recognize where epistemic commitments and styles of the students might be expressed. From this first round of analysis, we identified segments in which students might be engaging in computational tinkering. We then looked across these, discussed them as a research team, and characterized them in terms of material practices and conceptual work in which students were engaged. For three focal groups of students, we also described how work during these moments related to identities and dispositions surfaced during interviews and other activities.

Looking again across these moments, we identified three core activities - *play*, *troubleshooting* and *sharing* - that captured how computational tinkering appeared in the high school science classroom. We report on these activities, using close analysis of one group to illustrate them. We also used these three activities as codes through which to analyze activity in the second design round, refining our hypothesis around them as candidate forms through which computational tinkering is manifested in scientific learning. We coded student activity in an Exercise Lab and Flat Data Lab for these three areas, alongside codes for emergent goals, rapid iteration, and noticing, while leaving space for additional themes to emerge and for us to identity any instances of identity work or bricolage that fell outside these categories.

Findings

Design Round 1: Computational tinkering in project-based science labs

In Design Round 1, we designed for computational tinkering as part of introductory labs in which students first encountered and learned about how to use the sensor kit, and had open-ended time to use both sensors and actuators together. We hoped the introduction could provide new kinds of entry points into the unit, invite opportunities for design, feedback, reflection and iteration, and set the tone for subsequent investigations of plant photosynthesis and cellular respiration. The teacher, Mr. B, who had an orientation toward student-led inquiry, framed initial activities as a design challenge without a single answer, and maintained a communitarian ethos that valued divergent ideas, encouraged sharing, and legitimized material and technical, alongside conceptual, work.

In one focal group, Akeem and Maala were friends who worked together throughout the two weeks. They had a strong desire to put together a working system of sensors and relay, and to understand that system on their own, without direction from a teacher or peers. Akeem and Maala initially began by connecting and disconnecting hardware in order to understand what worked and what did not work. Once they were able to create operational systems, they moved each sensor around to create different looking datasets and try to understand how specific manipulations manifested in their data. Towards the end of the activity, Maala worked with another student at the table to try and create a "clapper"-like system to actuate a light by using a sensor. Maala would tell the other student to clap, then they would cover the light sensor so that the relay would turn off. Due to the time delay, it did not work immediately and they laughed at their efforts to coordinate clapping with the lamp.

As the group moved through investigations of cellular respiration and photosynthesis, Akeem and Maala decided to investigate the effect on CO_2 uptake of different starting CO_2 levels. They placed spinach leaves into a plastic Ziplock bag with a CO_2 sensor inside. Maala was initially the one who would blow air into the bag to try to create starting CO_2 conditions, but she would often blow too much air into the bag, causing them to run into the maximum value the sensor technology could measure. Akeem, oriented to the measurement aspects of their investigation, teased Maala about being bad at blowing into the bag. As they blew into the bag, they would watch the screen to see whether it hit the sensor maximum, then they would adjust or revise or try again. While an initial goal was to investigate plant respiration, other goals emerged as they became more familiar with their setups and sensors. They had planned to take data at specific numbers of breaths, but consistently hit a sensor maximum. They then tried to create 2,000, 4,000, and 8,000ppm intervals for their starting CO_2, breathing in a little, opening the bag and sealing it at the desired level. When they started at 8,000 they found that their CO_2 levels would still rise to hit the sensor maximum, so they adjusted their experiment again to be at even intervals. The data they produced was puzzling, with Akeem eventually arguing that his graphs should fit together spatially.

During their work in the introductory activity and investigations, the sensor kit's CO_2 maximum became a center of both troubleshooting and play, two types of activity that we saw develop as common sites of computational tinkering across the class. Avoiding the sensor max became a kind of game, with Akeem and Maala cheering as they watched their signal rise up to and hit (or not) the sensor max. In moments of play like this, new goals quickly formed and resolved, with students expressing joy and frustration, and thinking about new and divergent uses for the computational system. Across the unit, play took two main forms: first, creating game-like goals or tasks, like Akeem's and Maala's clapper, as well as, for example, efforts to create a "paradox" – a self-cancelling program – or to write a program that would turn off a relay being used by a friend. Second, students brought playfulness to non-game activities, as in Akeem and Maala's engagement with the sensor max. During troubleshooting, students relied on tight, real-time coupling between the data display on their computer screens, their experiment materials to figure out how to adjust to unexpected behaviors, such variations in data due to their set-up of materials, and to limitations or idiosyncrasies of the computational tools, such as the sensor max. Alongside this back and forth, students noticed and theorized, through explicit explanations and tacit adjustments

– such as trying to moderate the level of breath – possible biological, material and computational explanations of behavior.

Design Round 2: Supporting computational tinkering in lab investigations

Computational tinkering in the Flat Data Lab

In our curriculum sequence, students did labs where they investigated phenomena related to plant photosynthesis and cellular respiration. These two processes can occur simultaneously in plant leaves and their effects on carbon dioxide levels can reach equilibrium. However, many students believed that plants can do only one process at a time, and so such a balance should be impossible. In our Round 2 implementation, we designed an activity in which students were asked to create "flat data." Because there were many possible ways to accomplish this (including setting up materials *just right*, or dynamically responding to changing levels, either manually or programmatically via the software), we believed this activity would support the emergence of goals, rapid iteration, and noticing characteristic of computational tinkering.

Due to time constraints in other classrooms, only one teacher, Ms. Redick, was able to do the Flat Data Lab. She introduced the activity by saying that it was okay if students were not successful, as they tried something sensible and documented their thinking. From this class, the two focal groups we focus on here worked across from each other. In group 1, Ana asked the group what their design should be and decided that they should "put all this stuff" – light and CO_2 sensors and spinach – in a Tupperware container, cover it with plastic cling wrap, "put it in the sink and then put paper over it." As she gathered materials and began looking at sensor data on the software interface, Ana verbalized decisions and questions to her partner, Jesse, as well as to the two students in group 2, Victor and Isabel. Once the group's container was sealed, Ana turned the light on and watched the computer screen intently, her face close, as the sensor data began to generate a time-series graph.

Ana punctuated her close watching of the data by calling out when the data rose, fell, or looked like it might be staying flat, and by moving periodically back to the sink and container in response. This work, common across students in the lab, resembled the *troubleshooting* we observed in round 1, but was closer to something like *tuning*: Ana made slight adjustments to the lamp position and paper, checked the effect on the graph, and readjusted, at times running the short distance between her computer and the setup. Alongside Ana, Victor was going through the same steps, but worked quietly, doing small tests and tweaks: he moved the sensor around to see how the data responded before putting it in the container: he checked light levels, in addition to CO_2 levels, as he adjusted the height of his lamp. Victor eventually realized light from the other group's lamp may have been affecting his own group's set-up. In response, Ana retuned their setup by lowering her lamp closer to the sink, then added additional wax paper to negate the increased light intensity. Across the class, similar processes were common: highly engaged groups noticing, discussing and trying to account for many factors: how far a cabinet door was open, how to measure how wide it was open, and how heavy it was; how bright ambient light was and whether the program controls can be used as a "slider" instead of "switch" for the lamp. Late in the class period, two groups also realized that they could use the software to create thresholds that triggered the relay on and off, creating data that was stable, if not perfectly flat.

As they worked, students' engagement in the task to create "flat data" resembled Maala's playfulness. Ana frequently vocalized joy and frustration as the data stabilized for a time, then would rise or fall. Though the task was assigned, she seemed to be taking on this goal emotionally, as in a game, sharing it with others in the class, and taking pride or agony in the results of her performance. As she grew frustrated, Ana began to check in with Victor and other groups, asking, for example, "why is it dropping?!" as she looked at her screen, then turning to ask, "can I see your guys' data?" Perhaps given the nature of the task, Ms. Redick's framing, and this playfulness, movement across and sharing between groups was frequent.

In these moments of sharing, students engaged in aspects of computational tinkering. As they described their efforts, observed others, and asked each other questions, students encountered new ideas and articulated and negotiated the goal of the task, trying to decide what counted as success. For example, as students visited her table, Ana observed that "they [the two processes] were equal - for a split second." At a number of points she also stepped away to ask Victor and Isabel questions like, "did you get a *super* flat line? Like completely flat line?" As she used her arm to mimic the line, she continued, "ours keeps going between 1713 and 1720. It keeps going up and down." At the end of the lab, she said to Victor, Isabel, and Jesse, "I'm going to take this all apart now - I'm sad. Guys - this was a bust." Isabel declares, "I knew it wouldn't work - but, it depends on what you consider flat."

Computational tinkering in the Exercise Lab

In an Exercise Lab, designed for the Round 2 curricula, we asked students to determine whether there is more carbon dioxide gas in their breath when they exercise. In three classrooms, instead of prescribing methods for capturing data need to investigate this, we asked students to use available materials and design ways to capture, dilute and measure the CO_2 levels in their breath. Since this task, like Flat Data, allowed for many solutions and required avoiding the sensor maximum, we hoped it would encourage multiple trials and involve close, real-time observations of the data, and intended it to support the emergence of goals, rapid iteration, and noticing.

The group we focus on here, Jeff, Kristina, and Caleb, gathered supplies, including a supplemental resource sheet, and returned to their table. Perhaps unsure of where to start, the group immediately relied on the supplemental resource sheet and began their first runs by breathing into a small Ziplock bag, placing it into a larger bag that also held the sensor, then popping the small bag as they saved data from the sensor. This method allowed the air in the small bag, containing high levels of CO_2, to diffuse into air in the larger bag. Using this method, the group avoided hitting the sensor max and proceeded through the task prompts. Their data contained some unexplained artifacts, such a drops and "bumps" after hitting a peak value, and Jeff proposed one possible explanation – a leak in the bag – which they remedied by tightening the closure in next trials.

Kristina made multiple appeals to run additional trials to refine their set-up and replace the anomalous data. She first suggested that "we have to redo these, because this one's good, but this one is screwed up," eventually appealing with exasperation that "we can do it twice - we can do it as many times as we want." However, Jeff repeatedly refused, but swapped the small bag for a balloon, without discussing this with his lab partners. Kristina questioned the decision, asking "Why would we throw *balloons* in the bag? How would it make the data better?" Jeff again offered no explanation. Kristina asked this question multiple times over the next five minutes, and renewed her vigor when she saw that data produced using the balloon, "went so much higher." She wondered aloud, "why did that happen? What did balloon do?" Jeff answered, "probably because I have a lot of CO_2 in my breath." Kristina seemed to doubt this explanation – a biological explanation that contrasted with the material hypothesis she seemed to be forming – but her questions and efforts to discuss it were again ignored. When Jeff claimed that the worksheets did not ask them to answer what Kristina was asking, she replied, "but *I'm* asking." When Jeff eventually retorted that he did not know the answer to her questions and did not care, Kristina paused, smiled wryly, then pushed back from the table, shrugged and disengaged from her line of questions. When she suggested that they compare their data to other groups and reflect, as the worksheet prompted them to, Jeff said he did not think they needed to, since they had done the trials with the balloon and could compare to that.

In Kristina's efforts to redo their trials in response to the data, her appropriation of the goal to get better data, and her curiosity about different possible explanations for the variation in sensor data, we see forms of computational tinkering beginning to emerge. Yet Jeff's orientation to do only what was required by the task prompts cut these opportunities short. Despite putting in place some conditions for the emergence of new goals, for rapid iteration and new kinds of noticing, Kristina's efforts could not overcome this orientation, coupled as it was with power dynamics in the group - common to histories of gendered participation in STEM. This was not the case with all groups in the class. Though a number of groups engaged in the Exercise Lab in ways consistent with the focal group, we saw in others curious and playful engagement, brainstorming and discussing ideas as they moved through rounds of refinement, and wondered about how sensors were interacting with air.

Discussion

Though they did not appear uniformly across the activities and students groups, we have described three types of activity – *play*, *troubleshooting and tuning*, and *sharing* – in which computational tinkering appeared as episodes of 1) noticing and reflecting on behavior across the system, 2) movement back and forth across data, materials, and computational tools, and 3) emergent or shifting goals. While central, these features are not unique to computational tinkering, but they demonstrate how and where aspects of making and tinkering can appear as valuable practices within formal science education settings. They point to places where classroom teachers and educators might capitalize on interactions with computational systems – of which sensors are one example – to open space for epistemological pluralism and identity work. Here we discuss these activities in relation to professional science practice, as well as science education goals of supporting computational thinking, student agency, and epistemic pluralism.

Agency and epistemological pluralism in computational tinkering in science

As a prominent theme in the literature on tinkering, it is perhaps no surprise that we also found *play* appearing across many episodes of computational tinkering. While not all play that students engaged in was conceptually rich and related to the computational systems and/or task structure, we did see moments of play, such as in the work of Maala and Ana, that suggested that designing for computational tinkering had broadened space for relational work and ways of being within science. For instance, through play we saw the development of goals for scientific work that were tailored to individual preferences. In Maala's case, her work shifted from feeling obligatory to personal and emotional, with the possibility to share experiences with others and negotiate within a classroom community what counts as success (Kafai & Burke, 2014). In both cases, Maala's and Ana's engagement with the tasks and with the computational system became game-like, manifesting in expressions of joy and frustration. This emotional investment extended across both the material and scientific aspects of work.

Though the more formal, less student-centered, Round 2 implementation provided fewer opportunities for identity-linked orientations to emerge, we still saw room for students' epistemic agency, as evidenced by: (a) variation in students' epistemic strategies during data production, including forms of bricolage, (b) variation in sense-making, including considerations of different features of data representations, or attribution of features to the material world, biological phenomena, or their computational systems, and (c) orientations toward quiet, private experimentation (as with Victor) alongside more expressive, social engagement (as with Maala). However, as was clear in the Exercise Lab, we also saw occasions where attempts to direct inquiry and bring knowledge resources to bear were stifled. The introduction of a tinkering frame and novel computational tools did not always disrupt the practices and identity work oriented toward "doing school," or the hierarchies and position encoded into science classrooms, if not the larger institution of science.

Computational tinkering and scientific disciplinary practices

In moments of computational tinkering in science, we saw two kinds of noticing and reflection develop: first, and more frequent, of target biological phenomena, through use of the computational system, and second, of the computational system itself. The former was more prevalent, pointing to ways that computational thinking may provide benefit to existing disciplinary goals for science instruction – in this context, having to do with developing conceptual understandings of respiration and photosynthesis. The latter, though less common, led to curiosities about how computational tools worked, how they connected to each other, and how they interacted with the material world. These curiosities and observations were prompted by encounters with unexpected behavior (such as the sensor maximum, or delays and incongruities between virtual and real-world behavior of the system), or by a need to critically evaluate when data sufficiently represented phenomena. These noticings lay the groundwork for development of a stance toward technologies and data that is both critical and optimistic, seeing potential flaws and dangers, as well as potential value (see also Hardy, et al., 2019; Miller & Horneff, 2017).

Yet despite these opportunities, as a form of inquiry into the world (Resnick & Rosenbaum, 2013), computational tinkering activity remained largely focused on the behavior of the system, with students articulating fewer connections between observations of behavior and models of the scientific phenomena and computational system than we hoped. While some of these connections were made in follow-up discussions of data and scientific concepts, building from the students experiences, this nonetheless points to (1) areas of future research and support, and (2) limitations in how science education is conceptualized relative to professional scientific practice.

The pathways students took as they tried to *do*, rather than just *understand*, something resembled those described in studies of computational tinkering and making, in which inquiry takes unexpected turns (Pressice, 2017). They also resembled those of professional scientists as they engage with and reconfigure materials toward goals that may not be articulated until later (Pickering, 1995, Jaber & Hammer, 2016). Use of the sensor kit, like use of modeling software, allowed for traces that could be interrogated, revised, and used for collective sense-making, allowing students at an individual level to move from protocols that ensure easily interpretable results and to risk failure. These pathways in which individual, material and disciplinary agencies intertwine provide a context for developing epistemic agency that is increasing priority in science education (Miller, et al., 2018; Hardy, et al., 2019). Computational tinkering may look haphazard in relation to an idealized view of science as rational, abstract deliberation. But delaying articulation of detailed plans and hypotheses, and instead engaging in smaller cycles of trials, noticing and adjusting, may be of particular benefit to novices encountering technologies and concepts with which they have little prior experience (Resnick & Rosenbaum, 2013).

Implications

This study identified *troubleshooting and tuning*, *play*, and *sharing* as valuable forms of activity in which students may develop agency and accomplish identity work while learning to use computational tools as part of science practice. We also saw aspects of experience that were important catalysts for computational tinkering, such as violations of expectation, quick cycles of revision, and support for orientation toward many aspects of investigation, like design, materials, computation, system behavior. Despite current limitations of this study (and the instructional designs), we believe computational tinkering is critical to conversations about the integration of computational thinking in science. Designing spaces for computational tinkering allows for knowledge to build through and toward concrete, situated action, as learners, like scientists, adapt to unexpected resistances and imagine new possibilities. Computational tinkering may support: 1) new avenues of participation in science for young people who are builders and conveners (Turkle & Papert, 1990), 2) new relationships between learners, computational systems, and science practice, and 3) learning experiences with a quality or depth of emotion that students are usually told are not a part of science classroom, despite being a part of science (Jaber & Hammer 2016). As part of trajectory across many forms and contexts of computation participation, computational tinkering in science encourages us to rethink instructional designs for data production and theory-building in science as processes of doing and reflecting, not collection and analyzing. Science must be receptive to adaptation and creativity, in the face of unexpected results, new technologies and emerging priorities; science education should be as well.

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