Designing a Middle School Science Curriculum that Integrates Computational Thinking and Sensor Technology

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ABSTRACT

This experience report describes two iterations of a curriculum development process in which middle school teachers worked with our research team to collaboratively design and enact instructional units where students used sensors to investigate scientific phenomena. In this report, we examine the affordances of using a sensor platform to support the integration of disciplinary learning and computational thinking (CT) aligned with Next Generation Science Standards [13] and the CT in STEM Taxonomy developed by Weintrop and colleagues [31]. In the first unit, students investigated the conditions for mold growth within their school using a custom sensor system. After analyzing implementation experiences and student interest data, our team engaged in another round of co-design to develop a second instructional unit. This unit uses a different sensor system (the micro:bit) which supports additional CT in STEM practices due to its block-based programming interface and its real time data display. For the second unit we selected a different phenomenon: understanding and designing maglev trains.

KEYWORDS

Computational Thinking, Middle School Science, Sensors

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1 INTRODUCTION

Computational thinking (CT) and big data practices are having profound effects in all scientific domains and are fundamentally changing the ways scientists work. Exposing students to these practices not only gives them insight into these modern scientific practices but also introduces them to applications of computer science and data science.

States across the U.S. are increasingly adopting a new approach for K-12 science education called the Next Generation Science Standards (NGSS) [13]. These standards define science education in terms of three dimensions: science and engineering practices, disciplinary core ideas, and crosscutting concepts with the goal of making science classes more inquiry-driven and similar to the work of scientists.

However, a critical gap remains in understanding how to best integrate CT into NGSS-aligned science instruction beyond simply including more and bigger datasets or adding technological instruments. Instead, the goal is to provide students with ongoing experiences to advance their CT skills and support their understanding of how those skills are a fundamental aspect of contemporary scientific inquiry.

One promising approach is through the use small, mobile sensors [3, 8, 16]. Sensors have long been used to support the learning of computer science and computational thinking through tools such as LEGO Mindstorms™ and other robotics [14, 23]. As these sensors become increasingly low-cost and widely available, they are more accessible to teachers for classroom use. They can be instrumented to provide fine grained and continuous measurements of the physical world (e.g., temperature, magnetism) in order to explore scientific phenomena such as air quality [32] or information about the local watershed [15].

Moreover, research suggests that focusing on *place* can offer a powerful tool for engaging learners from underrepresented groups in STEM [1, 11, 19, 30]. Place-based investigations focus on personally relevant scientific phenomena or activities that address issues meaningful to the local community. Students consider *why here?* and *so what?* questions that provide local context for the phenomenon they are learning about [6].

As part of our research on integrating CT and sensor technology into middle school science curriculum, our goal is to design a coherent sequence of lessons that meet all of the criteria described above and represented in Figure 1 as "design constraints." To this end, we employ a design methodology that we label the CT-Integration Cycle, which involves developing, implementing, and reflecting on CT-integrated science units. The CT-Integration Cycle draws on

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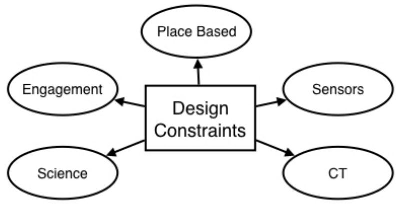

Figure 1: Set of constraints that influence our design process.

three strategies that have proven useful in developing NGSS curriculum: design based implementation research (DBIR), storylines, and collaborative design (co-design).

In DBIR, new educational interventions are developed and refined through iterative design cycles, involving field deployment and data collection [7]. DBIR emphasizes the cyclic nature of the design work where reflections from previous implementations influence the next development session. Moreover, a critical aspect of DBIR is on addressing key problems of practice in the target environment, in our case middle school science.

Storylines [20, 21] are a resource for developing science curricula that are meant to support NGSS alignment. Storylines provide an avenue for the integration of CT into science classes by explicating what science concepts students will "figure out" and which practices they will use to make sense of phenomena through a series of connected, student-generated questions. We use storylines as a central tool in our curriculum design because they encourage well-articulated learning experiences and are flexible enough to incorporate CT practices. We describe the storyline process in Section 2.1.1 .

A central tenet of our work is that the curriculum should be co-designed with teachers. Taking an active role in the generation of their own storylines and accompanying lesson materials ensures that teachers have a strong voice and sense of agency in the initiatives that affect their daily practice [12, 28]. We describe co-design in more detail in Section 2.1.2

This experience report details the first iteration of the CT-Integration Cycle in which students used a custom sensor system to investigate their school for the potential for mold growth by collecting temperature and humidity data. We reflect on the extent to which the first iteration met each of the design constraints listed in Figure 1 and on how our experiences throughout iteration one influenced a second CT-Integration Cycle with respect to the co-design process and the design constraints.

2 METHODOLOGY

Integrating CT into middle school science curriculum requires balancing a number of competing factors, such as those displayed in Figure 1. Below, we discuss the design strategies we used to meet these constraints along with the “Computational Thinking in STEM Taxonomy"[31] that heavily influences our work.

2.1 Design Strategies

We utilize two design strategies that have proven successful in developing NGSS-aligned science curriculum: storylines and co-design. We choose these strategies because they help ensure that the focal science content is addressed in a manner that provides a solid foundation for student learning. When designing curriculum that is intended to be implemented in mainstream science classes, it is especially important to demonstrate to stakeholder groups that discipline specific science learning is not sacrificed when additional components are added and ideally these additional components serve to enhance students’ science learning. In addition, we utilize sensors as an entry point for CT to ground the CT integration in students’ place.

2.1.1 Storylines. Storylines serve as unit guides and are created before individual lessons are written to ensure coherence as well as incremental knowledge building [20, 25, 29]. Storylines typically begin with a scientific phenomenon (e.g., how the moon affects tides) that is intended to "anchor" the unit. Students generate questions and ideas about the phenomenon and progress through a series of smaller questions, eventually leading them to be able to answer a bigger question or respond to a challenge [26]. In developing storylines, design teams strive to predict likely student questions and provide a sequencing of ideas and activities that sustains continuity and interest throughout the unit [21]. The aim is to help students feel and act like scientists or drivers of the scientific inquiry process, rather than simply as students who are learning about science [17]. Of critical importance is tying the anchoring phenomena to issues that are locally relevant and interesting for students, in order to support motivation and promote deeper levels of thinking [4].

2.1.2 Co-Design. Co-design has been used as a productive curriculum building experience [7, 28], especially for science curriculum [18], as a way to increase teachers’ engagement with and investment in the curriculum. The co-design process integratlly involves the teachers’ expertise when developing the storyline units, and helps ensures that the resulting storyline units are both feasible and appropriate for their local school context.

2.2 Computational Thinking Analysis Framework

While several frameworks exist for examining CT [5, 9, 22], we chose one that is designed specifically to work with integrating CT into STEM. Weintrop and colleagues [31] defined the “Computational Thinking in STEM Taxonomy” to provide a specific breakdown of what CT can look like in STEM classes. They identified four major categories of CT practices: *data practices*, *modeling and simulation practices*, *computational problem solving practices*, and *systems thinking practices.* They specifically chose the term "practices" to suggest their relatedness to the NGSS science and engineering practices. For iteration one, we focused primarily on the data practices category because it provides a familiar entry point for science teachers. For iteration two, we added several of the computational problem solving practices.

2.2.1 Data practices. Data practices describe the different ways that students should work with and understand data. Data practices involve collecting, creating, manipulating, analyzing, and visualizing data. These practices allow students to develop a deep understanding of how data can work for them to aid in their scientific investigations.

2.2.2 *Computational Problem Solving Practices.*

Computational problem solving practices are the portion of the taxonomy most closely related to computer science. These practices involve breaking down a question into parts that can be investigated using computational tools as well as choosing the best computational tool based on the assessment of different approaches to addressing the question. These practices also involve more traditional computer science principles of programming, modularity, abstraction, and debugging but applied to problems in mathematics and science.

While this framework provides a helpful basis for determining where CT exists in different STEM units, it lacks a suggested entry point for designing new units as well as a suggested sequences of practices. During iterations of the CT-Integration Cycle, we designed different potential sequences of practices.

3 CT-INTEGRATION CYCLE ITERATION ONE

Four middle school teachers from a large urban public school district (three science teachers and one integrated STEM teacher) participated in the first iteration of the project. In this district, integrated STEM is a required elective course that meets less frequently than regular classes and focuses on topics such as civil engineering, introductory programming, and electronics.

3.1 Development

The participating teachers attended three full-day professional development workshops throughout the 2017-18 academic year. During the workshops, they co-designed an NGSS-aligned storyline unit that incorporated a custom sensor system, prepared to implement the unit, shared and discussed videoclips from their implementation, and reflected on how to improve future units as well as the sensor system.

The storyline, outlined in Figure 2, was based on the driving question *Does our school have the right conditions to support mold growth?* As part of the unit, students were encouraged to consider: *(1) why and how does mold grow*, *(2) can mold grow in our school*, and *(3) how can we make our school less hospitable to mold growth.*

A custom sensor system was used to examine whether particular locations in the students' schools were favorable environments for mold growth. The system measured temperature, humidity, pressure, carbon dioxide, and total volatile organic compounds. Sensors were preprogrammed to collect data every second. Students could determine where to put the sensor and when to start and stop the data collection. To access the data, students copied it from the SD card on the sensor system to their computers. They used spreadsheet software (Google Sheets) to analyze and visualize the relevant data.

3.2 Implementation

Each teacher implemented the five-lesson unit in their classroom in Spring 2018. Within each class, groups of approximately four students each received a sensor system. The three science teachers completed the unit over a one-week period, whereas the integrated STEM teacher implemented it over a three-week period (because she saw her students only one or twice a week). A researcher was present for the first and last lesson. During the use of the sensor system, a researcher was present in the classroom if the teacher requested it (three of the four teachers did). Students ranged from 5^{th} grade to 8^{th} grade, were evenly split between girls and boys, and over 50% self-identified as Hispanic.

3.2.1 *Date Collected.*

We collected a variety of qualitative and quantitative data including: (1) video from the first and last lesson, (2) pre/post teacher interviews, (3) written teacher reflections, (4) student checkins from Lesson 1 and Lesson 5 (asking *What are you doing today?*, *Why are you doing this today?*, *How does what you are doing today relate to mold?*), (5) observational notes from Lesson 1 and Lesson 5, and (6) student artifacts.

As part of the curriculum, teachers collected student surveys at the end of each lesson. These brief, online surveys measured students' perceptions of the storyline, including whether they saw the lessons as coherent, relevant, and engaging.

3.3 Findings

In this section, we consider each design constraint in terms of the teachers' implementation of the storyline unit. Overall, the general impression from both the researchers and the teachers was that the mold growth storyline was sufficiently place-based and engaging to students, but that design elements related to the sensor system, science practices, and CT practices could be improved.

Place Based. Although the storyline was designed to be place-based (e.g., students explored their own schools), several teachers went even further than anticipated with their focus on place. Two teachers instructed their students to write recommendations to local stakeholders (principals, custodians) about mold growth in the school based on the data they collected. For example, one teacher prompted his students to argue for shutting down their school due to the possibility of mold growth. This teacher felt that a strong emphasis on place prompted his students to be more engaged than usual and peaked their interest in collecting data. Students of another teacher actually found mold and drew up a remediation plan, even offering to continue to monitor the affected area.

Engagement. Student survey data provides evidence that the storyline supported student engagement. Looking across the unit, 64.5% of students reported that the lessons mattered to them and 73.5% reported that the lessons mattered to their class. In addition, a majority of students (58%) felt excited about the lessons and almost half (49%) stated that they felt like scientists during the lessons.

Sensor System. The custom sensor system created for the teachers' implementation of the mold growth storyline functioned solely as a data collection mechanism. The system allowed students to collect all possible data from the embedded sensors, with a sampling rate of every second. Students simply pressed the sample button to start data collection and pressed it again to stop data collection. Thus, the system only supported the *Collecting Data* CT Practice. Furthermore, teachers reported that the sensor system was not especially user friendly and students' only feedback that data was being collected was a flashing green light.

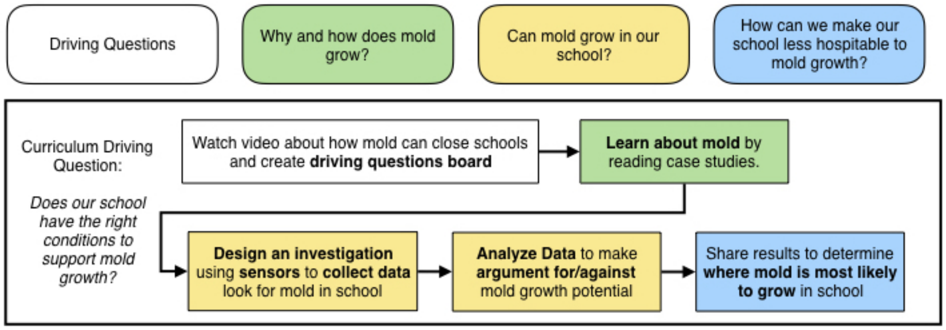

Figure 2: Storyline of the mold unit that addresses the question: Does our school have the right conditions to support mold growth? The bold text in the graphic refers to NGSS Practices and CT Practices.

NGSS Science Practices. The mold growth storyline was quite short and targeted only a portion of one disciplinary core science idea about organism growth in given environments. The storyline did include a relatively large emphasis on student engagement in science and engineering practices, such as students asking questions along with planning and carrying out an investigation to determine the potential for mold growth. Throughout the unit, students created written products that incorporated the cross cutting concepts of cause and effect as well as modeling.

Computational Thinking Practices. With respect to CT, the storyline focused mostly on data practices. Emphasizing data practices fit well with the capabilities of the existing sensor system and was a familiar entry point for the participating teachers. The students *collected* data using the sensor system and uploaded the data to their computers. Their next tasks were to *manipulate* the data to only display the relevant information (temperature and humidity), *analyze* the data to determine if the environment supported mold growth, and then create a *visualization* communicating the results of their analyses. The majority of students successfully undertook these tasks. However, we noted important differences in implementation of these practices between the Integrated STEM teacher and the science teachers. For example, the Integrated STEM teacher highlighted the appropriateness of various visualizations and helped her students learn how they could use visualizations to communicate what the data meant. The science teachers, on the other hand, placed more of an emphasis on the students' final answers rather than carefully attending to the analytic process.

3.4 Reflection

The first iteration of the CT-Integration Cycle, which included the development and implementation of the mold growth storyline unit, generated a wealth of information about how to integrate CT into science curriculum that addresses specific design constraints and culminates in a positive learning experience for students. Five lessons learned from this iteration were:

(1) More information needs to be provided to teachers about what is expected when implementing CT practices.
(2) Highlighting the place-based aspect of scientific investigations supports student engagement.
(3) A custom sensor system may support limited CT Practices.
(4) Exploring the conditions for mold growth in a dry climate over a limited timeframe may not provide variable or especially interesting data.
(5) A one week unit is likely too short to meaningfully implement many science and CT practices.

4 CT-INTEGRATION CYCLE ITERATION TWO

The second iteration of the CT-Integration Cycle is currently in progress, taking place during the 2018-2019 school year. Our project team is working with the same school district as in iteration one. For this iteration, there are six participating teachers: two returning teachers (one science and one Integrated STEM), plus four additional teachers (three science teachers and one Integrated STEM). Below, we describe a new storyline unit currently under development that focuses on understanding and designing maglev trains. We provide information about each design constraint related to this new unit, taking into account our experiences from the first iteration of the CT-Integration Cycle.

4.1 Co-Design

The first iteration of the CT-Integration Cycle began in Fall 2017 and did not include a summer component where teachers participated in the development of a storyline unit from scratch. Rather, the research team played a larger role in the initial design of the mold growth storyline, with the teachers acting as co-designers by critiquing and adapting the storyline and related instructional materials.

A critical element of the second iteration of the CT-Integration Cycle was a three-day workshop during Summer 2018 which enabled both researchers and teachers to more collaboratively develop the initial maglev train storyline. The teachers reported feeling heavily invested in this process and the two returning teachers took on larger roles as leaders in the workshop. One teacher mentioned they enjoyed the "progressive and innovative nature of what all of this [co-designing unit] with sensors offers." Overall the teachers valued the collaborative nature of the process. As one teacher expressed: "Each person in our group brings a different aspect to our team... this has allowed us to develop a much more solid storyline than any of us could have done alone."

4.2 Development

During the summer workshop, the teachers and researchers worked together to develop a storyline unit to answer the question: *how do maglev trains works?*, with careful consideration given to the design constraints shown in Figure 1. The development process led to a detailed outline with a sequence of lessons for the unit, to be later fleshed-out by the research team. Additionally, the research team will create lesson plans and other instructional materials, with multiple opportunities for the participating teachers to provide input and suggest revisions prior to their implementation, see Figure 3. The maglev storyline unit is targeted to be implemented over a three-week period and thus has significantly more depth in the coverage of the science content, CT practices, and sensor use compared to the mold growth storyline unit.

In the maglev train storyline unit (see Figure 3), students investigate the electromagnetic forces that enable a maglev train to levitate and serve as a propulsion mechanism for the train. The students build a variety of models and used the sensors on the micro:bit (described below) to investigate magnetic fields created by simple magnets, electrical circuits, and electromagnets to gather evidence that will help them explain how a maglev train functions. Students utilize CT and engineering design processes to apply the science concepts to create an efficient, fully functional scale model maglev train. Lastly, they write a proposal for why a maglev train should be built in their community using all of the information that they have learned throughout the storyline unit.

Place Based. Similar to the mold growth unit, a central goal in developing the maglev train unit was to incorporate place in a meaningful way for students. To do so, a focus throughout the unit is on how maglev trains serve local communities. For example, the unit incorporates videos and other information about the function and benefits of existing maglev trains, and students write a proposal for the installation of a maglev train in their own community.

Engagement. Whereas in the first CT-Integration Cycle, the research team selected mold growth as the focal phenomenon, there was a more collaborative and inclusive process for selecting the focal phenomenon for the second iteration. The research team and the teachers discussed multiple candidate phenomena and created an interest survey asking students which of eight phenomena they found most interesting and relevant. Results from the survey indicated that students' top two choices were maglev trains and color changing playgrounds. The teachers then engaged in a sustained exploration of both these options, and agreed that maglev trains held the most promise in terms of meeting all of the design constraints. In prior work, developing learning activities based on phenomena identified through these measures has proven an effective strategy for ensuring the engagement of diverse students in high school biology [17].

Sensor System. The design of the custom sensor did not readily support CT practices other than *Collecting Data.* Going forward, we wanted to utilize a sensor system that could support additional CT Practices and had additional benefits over the custom system. Thus, in iteration two, we elected to use the micro:bit, a microcontroller designed for educational use. Micro:bits are becoming increasingly popular as part of an introductory computing experience [24, 27]. The micro:bit contains a variety of onboard sensors including a magnetometer and an accelerometer, with additional sensors being developed by our industry partner. The micro:bit is relatively low cost (presently costing less than $20 compared to the original sensor system which was approximately $175), portable, and does not require external software installation to program (an important consideration when working with schools). It is easily programmable in both block and text based languages [2, 10], which will allow students to have more control over the data collection process and better incorporate the *CT Computational Problem Solving Practices.* Data can be collected using the micro:bit and transfered to a computer and/or displayed using the LEDs on the micro:bit, thus allowing students to see the data in real time as it is collected. For the maglev storyline unit, the students will program the magnetometer sensor on the micro:bit to measure the magnetic fields created by static and electromagnets. In addition, the accelerometer will be used when the students design a train car that meet various constraints, see the Figure 3. All of the data students collect can be displayed on the micro:bit in real time and also recorded to their computers for later analyses.

NGSS Science Standards The increased length of the maglev storyline allows for more science standards to be included and for the unit to go more deeply into these topics as compared to the mold storyline. The maglev storyline incorporates four science performance expectations involving forces, motion, and electromagnetic fields. The *Cross Cutting Concepts* include cause and effect, systems and system, and stability and change. The *Science and Engineering Practices* include asking questions and defining problems, planning and carrying out investigations, constructing explanations and designing solutions, and engaging in an argument from evidence.

Computational Thinking Practices. The increased length of the maglev train storyline unit relative to the mold growth storyline also allows for more time to be spent on CT practices. The students will *program* the magnetometer sensor on the micro:bit to *collect* information about the magnetic field strength, which will help them *visualize* the strength of magnetic field. They will also *program* the LEDs to display the data on field strength. When investigating the electromagnets, students will *analyze* the data *collected* to see how coiling copper wire creates a stronger magnet. While programming the micro:bit, the students will involve the additional computational problem solving practice of *debugging*.

4.3 Reflection

The development of the second iteration of the CT-Integration Cycle builds off lessons learned from iteration one: the design constraints listed in Figure 1 necessarily narrow the set of candidate phenomena, the robust design of a sensor system is important, an investigation of the phenomenon should involve data that is variable, and students benefit from getting real time feedback when they are collecting data.

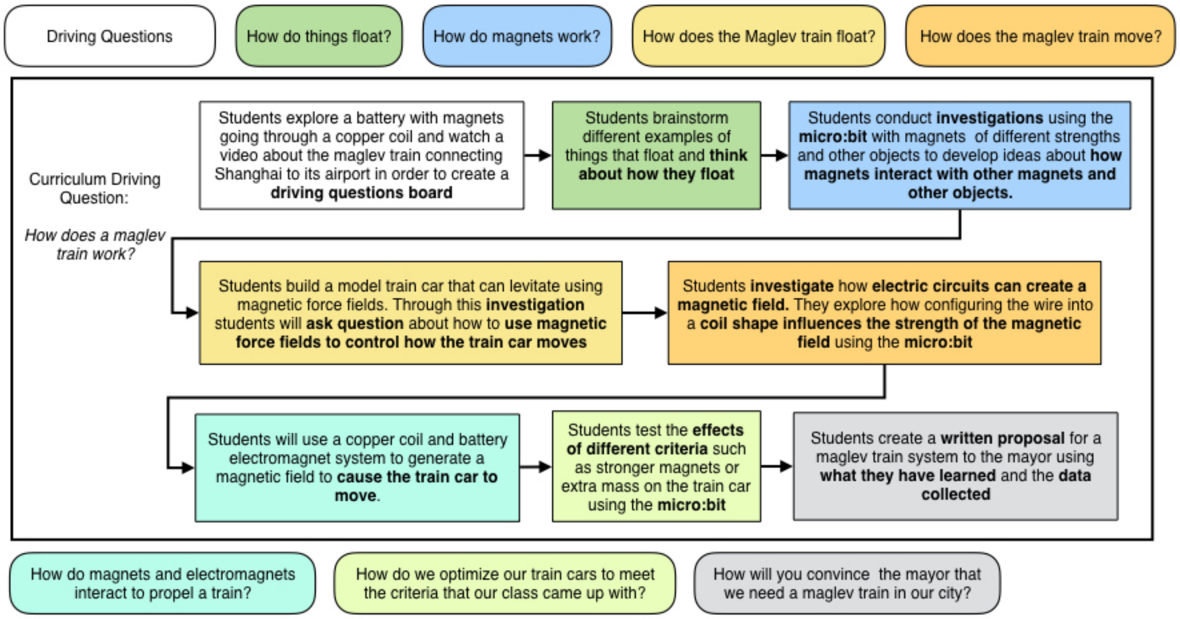

Figure 3: Draft storyline of the maglev unit: How does a maglev train work? The bold text represents NGSS and CT Practices.

The teachers who have participated in our research have been clear in their desire to deeply understand CT, to learn ways to apply CT in their classes, and to help create resources that support CT integration for the K-12 education landscape as a whole. Goals for iteration two include capturing teachers' evolving understanding of CT and ensuring that both the science teachers as well as the Integrated STEM teachers deeply integrate CT Practices with disciplinary instruction. Along these lines, some topics that we plan to address with the teachers are developing a common vocabulary for core CT concepts, explicating that CT does not simply mean coding, and articulating the vertical (between grades) and horizontal (between subjects) integration of CT in K-12 classrooms.

5 LESSONS LEARNED

Designing science curriculum that integrates CT and incorporates all of the design constraints in Figure 1 requires thoughtful design choices and collaboration. We found the utilization of storylines to be an effective tool for to developing coherent, NGSS-aligned CT integrated units. In addition, the co-design process allowed teachers to have a strong agentic voice in the direction of the storylines.

Although selecting appropriate scientific phenomenon to anchor a storyline is always a critical first step, an important lesson learned from our work is that the use of sensors means that the set of potential phenomenon is necessarily restricted. The selected phenomenon should not only match the capabilities of the available sensors, but it should allow for the collection of relevant data over time so that the analyses and sense-making from the data help move the unit forward. Furthermore, we found that CT practices can be best incorporated if the data is variable in nature and if the sensors can be programmed by the students. In this way, the sensors would support a variety of meaningful CT practices and serve as more than simply a preprogrammed data collection tool.

In addition, just like a single unit cannot support all of the science and engineering practices, it also cannot target all of the CT practices. In terms of designing curriculum to enable a trajectory of CT learning, we found it helpful to start by incorporating the CT *Data Practices*, such as collecting, manipulating, analyzing, and visualizing data. These practices provide a familiar and comfortable entry point for both science teachers and their students, both of whom often do not have much programming experience.

Finally, to effectively integrate CT and sensors into science curriculum, on-going professional development and curricular resources, like the ones we are developing, are essential components.

6 CONCLUSION

We were successful in developing storyline units that met a relatively large number of specific constraints: they had to be place-based, engaging to students, use sensor technology, align with the Next Generation Science Standards, and incorporate CT practices. The co-design process involving both researchers and teachers together with an extended reflective process helped to ensure that all of these constraints were met. Over the next year, as we engage in the second iteration of the CT-Integration Cycle, we will continue to develop and revise the maglev train storyline unit. Ultimately our goal is to generate a set of building blocks together with explicit guidance for others who are seeking to integrate CT and sensor technology into mainstream science classes.

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