Thinking Thru Making: Mapping Computational Thinking Practices onto Scientific Reasoning

Colby Tofel-Grehl1 · Kristin A. Searle2 · Douglas Ball1

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Abstract
This paper shares findings from a teacher designed physics and computing unit that engaged students in learning physics and computing concurrently thru inquiry. Using scientific inquiry skills and practices, students were tasked with assessing the validity of local rollercoaster g-force ratings as posted to the public. Students used computational electronic textile circuits (e-textiles) to engage in “myth busting” amusement park g-force ratings. In doing so, students engaged computing and computational thinking skills in service to answering their scientific inquiry. Findings from this study indicate that physics classes are ideal spaces for engaging in computing’s Big Ideas as laid out by Grover and Pea (Educational Researcher 42, 38–43, 2013) as well as the pillars of computational thinking (Wing, Communications of the ACM 49, 33–35, 2006). However, essential to this dual engagement is a need for computing content to act in service to the better acquisition of physics content within the physics classroom space. Findings indicate that the teachers’ use of e-textiles to integrate physics and computing broadened and deepened student learning by providing affordances for computational thinking within the structure of physical science inquiry.

Despite growing efforts to bring formal computer science (CS) education into high school settings (e.g., CS4All), progress has been limited, with most dedicated CS classes available only as AP or elective courses. Further, nearly half of states in the USA do not count CS courses toward high school graduation requirements (Bass & DeJong, 2020), and more than half do not offer a CS certification option to teachers as part of their state teaching licensure (Stephenson, 2015). Accordingly, students’ opportunities to learn CS skills and concepts as part of their core curriculum and teachers’ preparation to engage them in CS is limited (Nager & Atkinson, 2016). Computer science education and integration are further complicated by overcrowding of the curriculum. Teachers already report not having enough instructional time to teach all of the existing content they are responsible for (Majoni, 2017) and, as such, are wary of adding additional content areas such as computing. The interaction between systemic institutional barriers and barriers related to teacher choice and belief create significant obstacles for the full integration of computing within content classrooms (Makki et al., 2018). These findings and others indicate a need for scaffolded approaches for integrating computing into already existing and required standards.

Furthermore, despite decades of calls for inquiry as an essential aspect of science instruction (Windschitl, 2003; National Research Council, 2012), including within the Next Generation Science Standards (NGSS), evidence indicates that very little inquiry takes place in science classrooms (Capps et al., 2012). When teachers do provide inquiry opportunities, they typically do not engage with it in a deeply informed or authentic way, resulting in limited understanding for their students (Lederman et al., 2014). Consequently, students develop a limited view of what science is and fail to fully develop critical inquiry skills that would prepare them for advanced study or the scientific workforce. However, studies indicate that professional development can be effective in fostering improved inquiry practice at the secondary level and technology integration can help (e.g., Lawless & Pellegrino, 2007; Penuel et al., 2007). The NGSS provide a...
promising platform to thoroughly integrate science, engineering, and mathematics practices (Krajcik & Merritt, 2012). Although inquiry encompasses a wide variety of activities designed to engage the learner more deeply with the intended content (e.g., problem-solving, modeling, hypothesis testing, etc.; Windschitl et al., 2008), there is broad consensus among science education researchers that much school-based instruction currently in use is deficient in fostering authentic practice (Braund & Reiss, 2006; Lederman et al., 2014).

When instruction does emphasize open-ended inquiry experiences and makes scientific reasoning an explicit goal of instruction, student achievement improves for students across demographic backgrounds (Von Secker & Lissitz, 1999; Zohar & Nemet, 2002).

This failure to integrate computing and science inquiry as a common instructional practice is frequently attributed to two major barriers (Bingimlas, 2009). First, teachers often lack sufficient content knowledge to span separate content areas such as science and computing (Aldunate & Nussbaum, 2013; Ertmer et al., 2012). Second, very few models of systematic integration are available to guide teachers’ classroom practice (Kreijns et al., 2013; Repenning, 2012; Smolin & Lawless, 2007). While there are ongoing efforts to develop college preparatory computer science curricula (Grover & Pea, 2013), these approaches and materials do not engage an integrated approach to other content and do not translate easily to formal k-12 learning environments and standards.

The purpose of this study is to explore the affordances and challenges for science teachers to integrate CT practices into core science content within high school physics. Under the constraints of accountability to mandatory standards, teachers are often reluctant to expand the scope of the content they cover (Dougherty, 2013). Accordingly, the incorporation of additional elements must provide a compelling ability to better meet their instructional goals. To address the above noted challenges of computing and science integration, this paper examines the affordances for, and intersections of, integrating computing and physics within the high school setting. We examine the developing connections across science inquiry and computing to meet core instructional goals. Findings highlight the ways in which integrated curricula can create meaningful opportunities for students to participate in authentic computing and scientific inquiry that meet the requirements of a standards-driven accountability context.

Research Questions

With these understandings about the current state of computing and science integration in mind, we explore the following questions:

1. What opportunities to engage in computing ideas and practices occur within physics inquiry? In what ways, if any, do computing ideas and practices map on to behaviors observed during physics instruction that incorporates e-textiles?

2. In what ways, if any, can coding and computing be used to enhance instruction in physics classes?

Making as a Context for Integrated Curriculum

Integrated curriculum is used to incorporate essential learning skills across subject areas (Vars & Beane, 2000). Proponents of integrated curriculum promote the benefits of this approach, which include encouraging students to become involved in and aware of their learning and understand how this learning relates to real-world experiences (Huntley, 2002). Several meta-analyses have shown that students’ learning within integrated curriculum do as well as, if not better than, students in separate subject curricula (Beane, 1995). Hartzler (2000) compared 30 different integrated school studies and found an overall positive effect size of $d = 0.48$ (i.e., medium effect per Cohen, 1988) for increases in student achievement. Additionally, she concluded that these effects held regardless of the socioeconomic status of the student, the grade level, length of study, or the type of program.

When students encounter a topic several times for different reasons and in different situations, they create multiple representations, which lead to greater cognitive flexibility and transfer (Eilam & Yarden, 2007). Students cross-categorize skills and concepts to create flexible representations that raise capacity for higher level information processing and performance (Anderson, 1993). For example, the use of integrated math courses predicted increased math achievement beyond gains associated with reform-based instructional practices alone (McCaffrey et al., 2001). Similarly, Nelson (2007) found that the use of integrated curricula increased mathematics pass rates across all levels of socioeconomic status.

Making has emerged as an effective approach for introducing computing to students (Buechley, 2013; Peppler & Glosson, 2013; Tofel-Grehl et al., 2017). Because making provides students the opportunity to personalize designs and artifacts to reflect their own preferences and sense-making, no single design solution is inherently correct, and students may find many pathways to making their particular project work (Fields et al., 2012). Because making provides multiple solution pathways, it is well aligned with the goals and objectives of inquiry education as laid out in the NGSS.

Conventional breadboard activities, such as building parallel and series circuits, typically represent the lowest form of inquiry, confirmation (Bell et al., 2010), because they only require students to verify that the provided design works...
and do not offer opportunities to solve real world problems or resolve their own questions. Inquiry in NGSS is instantiated through eight science and engineering practices and the knowledge associated with those practices, including asking questions and defining problems, developing and using models, planning and carrying out investigations, analyzing and interpreting data, using mathematical and computational thinking, engaging in argument from evidence, and obtaining, evaluating, and communicating information. Thus, computing practices, a subset of Brennan and Resnick’s (2012) model for assessing computational thinking, are well-aligned with science and engineering practices in the NGSS: Students engage in incremental and iterative problem solving as they develop both code and the circuits controlled by the microprocessor; they engage in testing and debugging as part of that process; they reuse and remix existing code samples and models of basic circuits; and they abstract and modularize patterns that permit both sequential and parallel operations within the e-textile artifacts. Prior work on making in the classroom indicates that student learning, interest, and STEM identity are all enhanced when making is compared to business-as-usual science instruction (Tofel-Grehl et al., 2017, 2020). Furthermore, making in the classroom has been found to shift teacher instructional practices in ways that improve student beliefs about their own ability (Howell et al., 2016). Findings from these studies indicate that one of the key affordances of making in science classes is to shift the classroom discourse to a more student centered, inquiry driven model (Tofel-Grehl et al., 2020). With an emerging body of work indicating that making possesses unique and important affordances for classroom instruction, understanding the ways that computational making can support scientific inquiry is vital.

Methods

This study engaged a quant-QUAL exploratory mixed methods analysis. Data collected were qualitative with an exploratory quantification of some data to ground further qualitative analysis. Because of a lack of prior work on using computing to engage students in standards-based physics learning, we employed a grounded theory analytic approach (Lincoln & Guba, 1985) to understand the affordances of engaging computing through e-textiles to teach physics.

Data were analyzed iteratively and member-checked with the teachers for comprehensive understanding. Broad codes were identified then grouped into common themes and accreted into trends. Our work is framed and informed by the lens offered in Grover and Pea (2013). Specifically, we made sense of data in part by using the CS principles they laid out and how they were or were not applied within student engagement opportunities. From there, we explored the tangible and observable actions that did or did not map onto Wing’s (2006) elements of CT.

Setting

School

Solstice Educational Environmental Day School (SEEDS) is a large suburban high school located outside of a large city in the intermountain west region of the United States. Serving nearly 2200 students annually, the school regularly ranks among the top 25% of high schools in the state. Approximately 40% of students qualify for free and reduced lunch.

The Teachers

Mr. Volta (pseudonym) was entering his fifth-year teaching high school physics in a public, suburban high school in which 40% of students qualify for federal free and reduced lunch. Having received his undergraduate degree in his content area of physics, he opted to gain his teaching license through an alternate route to licensure program at a local university. Two years into teaching, he attended a professional development workshop at that university. He then opted to attend the professional development workshop a second time in order to learn new projects and help facilitate more of the physics content standards for his fellow teachers. He recruited the second teacher, Mr. Kirchhoff (pseudonym) to join him the second year for professional development. Mr. Kirchhoff was a third-year teacher at the same school as Mr. Volta. Both teachers worked together to cover all sections of physics at their local high school. Both teachers are white males in their mid-thirties.

Our participating teachers engaged in a weeklong professional development workshop that scaffolded teachers in learning both the conceptual knowledge needed in both content areas as well as the procedural knowledge necessary for construction of the maker projects. The professional development engaged worked examples and faded scaffolds to support teacher learning. It is worth noting that on pretests of relevant science content knowledge both teachers engaged in this study demonstrated stronger than average science content knowledge at the start of the professional development. This is not surprising given their specialization as physics teachers. Both teachers also reported prior experience with coding but did not demonstrate strong computing knowledge prior to professional development. Posttest results showed that both teachers demonstrated content knowledge growth in both computing and science content after completing the professional development. Further, though their designing, constructing, coding, and debugging of a series of e-textiles projects, the teachers demonstrated their acquisition of target content knowledge and integration, especially around computing.
Students

The students engaged with these projects are the physics students enrolled in Mr. Volta and Mr. Kirchhoff’s physics classes. A total of approximately 186 students divided across 7 sections of physics and honors physics were taught using e-textiles.

The Project

As noted earlier, two major barriers exist to computing and science integration (Bingimlas, 2009). Because teachers often lack sufficient content knowledge to span separate content areas such as science and computing (Aldunate & Nussbaum, 2013), our project begins with integrated computer science and physical science content training for teachers.

Beyond teacher knowledge, the second noted barrier to computing and science integration is a lack of model integrated curriculum that can guide teacher practice (Kreijns et al., 2013; Repenning, 2012; Smolin & Lawless, 2007). As part of the professional development and scaffolding, teachers were provided a fully scaffolded curriculum that moved them from introductory circuit construction into designing, coding, and constructing functional and purposeful computational circuits that addressed science content standards. With a well-articulated and explicated model curriculum, our teachers felt able to move forward and expand their own practice. Mr. Volta and Mr. Kirchhoff worked together to design an open-ended, scaffolded inquiry project for their students. Having attended the professional development training, the teachers modified the final project from that curriculum to one that allowed students to collect and analyze g-force data during an annual physics class field trip to a local amusement park to collect their data. This assignment was dubbed Roller Coaster Mythbuster Day (RCMB). The teachers framed the activity as a data collection and inquiry effort to determine if the safety and g-force ratings of the rides were accurate. From this limited framing and with a brief introduction to some of the common myths about forces around roller coasters, students developed their own inquiry questions and designed projects to answer them. Students sought to determine if the g-force listings on rides were accurate, if different types of rides exerted different types of forces, and if position within a roller coaster cart influenced the amount of g-force felt by people. In addressing these questions, students designed and built accelerometer sensor e-textile t-shirts, coded them to measure different changes in g-force, and then visited a local amusement park to collect their data. Students used the accelerometer’s reading of 9.8 m per second per second (m/s²) to be considered 1 g on the g-force scale, and any multiple of this value would be considered a multiple of g (e.g., 1 g, 2 g, 3 g etc.). The g-force, or gravitational force equivalent, is a metric to measure acceleration and named so because of the perception of force similar to the gravitational pull when accelerating at 9.8 m/s². The state science standards were addressed both in the lead-up to the event and during RCMB itself (see Table 1).

Data Sources

We used several data sources to complete this analysis. Each data source was compared to other data to check for counter examples or discrepancies. Data collection continued until saturation was reached and the research team felt they had made meaningful and accurate sense of the information presented them.

Observations

Both Mr. Volta and Mr. Kirchhoff’s classes were observed by the research team. Class observations were video and audio recorded. Student engagement at the roller coaster park was also observed and, when possible, recorded.

Interviews

Teacher reflections and interviews served as a primary source of data for this analysis. The teacher engaged in regular interviews and discussions with the lead research team member. Interviews were conducted jointly and separately to ascertain differences in perceptions of teachers. Interviews focused on understanding the process and thinking that went into the teacher team’s process for building from the provided curriculum.

Communications

Conversations, emails, and other communication with the teachers were also used for clarifying and following up on lines of inquiry.

Documents and Artifacts

When possible, lesson plans, student worksheets, project photographs, and other documentation of instruction were collected to serve an explanatory role in understanding the success of instruction.
| Tasks and timing                                      | Curriculum standard                                                                 | Standard objectives                                                                                                                                 |
|-----------------------------------------------------|--------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|
| E-textiles Instrumentation Design and Development in preparation for RCMB | **STANDARD III:** Students will understand the factors determining the strength of gravitational and electric forces | **Objective 2:** a. Describe the factors that affect the electric force (i.e., Coulomb’s law)  
   a. Relate the types of charge to their effect on electric force (i.e., like charges repel, unlike charges attract)  
   b. Describe how the amount of charge affects the electric force  
   c. Investigate the relationship of distance between charged objects and the strength of the electric force  
   d. Research and report on electric forces in everyday applications found in both nature and technology (e.g., lightning, living organisms, batteries, copy machine, electrostatic precipitators) |
| Data Collection and Analysis during and following RCMB | **STANDARD I:** Students will understand how to measure, calculate, and describe the motion of an object in terms of position, time, velocity, and acceleration | **Objective 4:** Use Newton’s first law to explain the motion of an object  
   a. Describe the motion of a moving object on which balanced forces are acting.  
   b. Observe and describe forces encountered in everyday life (e.g., braking of an automobile—friction, falling rain drops—gravity, directional compass—magnetic, bathroom scale—elastic or spring)  
   c. Measure the forces on an object using appropriate tools |
| Data Collection and Analysis during and following RCMB | **STANDARD II:** Students will understand the relation between force, mass, and acceleration | **Objective 1:** Analyze forces acting on an object  
   a. Describe the factors that affect the electric force (i.e., Coulomb’s law)  
   b. Observe and describe forces encountered in everyday life (e.g., braking of an automobile—friction, falling rain drops—gravity, directional compass—magnetic, bathroom scale—elastic or spring)  
   c. Measure the forces on an object using appropriate tools |
Data Analysis

Before exploring the ways in which students engaged with computing and computational thinking within a physics class, we needed to understand what opportunities they had for such engagement. Thus, before examining students’ ability to grapple with the pillars of CT, we first looked broadly at whether engagement with physics content through e-textiles provided meaningful opportunities to engage with Grover and Pea’s (2013) “Big Ideas” of computing. Grover and Pea identified seven discrete “Big Ideas” for computing: (1) computing is a creative human activity; (2) abstraction reduces information and detail to focus on concepts relevant to understanding and solving problems; (3) data and information facilitate the creation of knowledge; (4) algorithms are tools for developing and expressing solutions to computational problems; (5) programming is a creative process that produces computational artifacts; (6) digital devices, systems, and the networks that interconnect them enable and foster computational approaches to solving problems; and (7) computing enables innovation in other fields, including science, social science, humanities, arts, medicine, engineering, and business. If students engaged in these big ideas during their science inquiry learning, it would be indicative of greater overlap and opportunities for integration across physics and computing. These big ideas also represent broad strokes engagement with computing as a mediated tool for human learning and were thus our starting point. Engaging classroom observational data for the instruction and construction portions of the class over multiple weeks, we looked to see how many students appeared to have opportunities to engage in behaviors that reflected that big idea or aspect of CT. As a first mechanism for understanding these observations, we quantified these opportunities by percentage of students observed to engage or have the opportunity to engage in behaviors associated or reflective of specific Big Ideas.

After quantifying these opportunities for engagement, we dove deeper into understanding what the presence or absence of these Big Ideas looked like, noting specifically what behaviors students engaged in when they had such opportunities, and what the implications of them meant for students. We then engaged that same approach and process for Wing’s computational thinking practices with specific attention to noting where and when these practices aligned with associated NGSS practices. Finally, we open coded the data for integration of physics and computing with a focus on looking for affordances or unique learning opportunities that arose.

Findings

RQ 1: What opportunities to engage in computing ideas and practices occur within physics inquiry? In what ways, if any, do computing ideas and practices map on to behaviors observed during e-textiles instruction during physics class?

In seeking to understand the ways in which computing might be engaged within a physics classroom, we first examined the data through the lens of CT as laid out by Grover and Pea (2013). Specifically, we examined the data to determine if students had opportunities to engage in CT practices during their project design and coding processes; such opportunities would speak to a potentially unique set of affordances of e-textiles to allow students to simultaneously engage in CT and physics learning. If a substantial proportion of students had such CT engagement opportunities and demonstrated engagement with them, we could then look at the compatibility of CT practices and concepts with science learning within a standards-based environment, in this case a classroom. In this way, we could begin to explore the ways in which coding and computing might improve or support content learning within physics classes.

We characterized these percentages as All (100%), Near All (80–99%), Some (40–79%), Very few (1–39%), or None (0%). Table 2 explicates the presence of these big ideas as related to student experience with example behaviors.

It is important to note that during this inquiry project, 5 of the 7 Big Ideas of Grover and Pea are present for at least 80% of students. This means that a substantial majority of students engaged with most big ideas in computing, which suggests a very strong opportunity for teachers to engage students in meaningful integration of computing and physics. While students had rich and frequent opportunities to engage with these tenets, there were no observable discussions or engagement with algorithms. We queried the teachers about this, and one noted that algorithms were not needed for the physics content and inquiry goals of students. As Mr. Volta explained:

Algorithms don’t really come up [in physics]. Like, they are not part of the science content. I mean, we used them in the code, but I didn’t call it out as such. We do a lot of math in physics and the kids kinda get sick of it. So I wanted this to be fun and kept it simple. If it [use of algorithms] had been in service to the science I would have. But it didn’t really fit.
This teacher’s comment speaks to several important perceptions. He asserts that the only computing engaged within his classroom is that which is in direct service to the science, which confirms our earlier supposition that computing must be in service to content if teachers are going to engage and value it. The aspects of coding that he engaged most clearly in the project assignment he designed for his students related directly to the core content. Other aspects deemed less valuable for the instruction of the science were skimmed over or moved past. This makes sense when considering the goals of the teacher and student achievement targets linked to the curriculum standards by which he is evaluated. With standards-based education pressuring teachers to focus more energy on the tangibly evaluated knowledge and skills on which students are assessed, it stands to reason that aspects of coding which tie less tightly to the outcomes sought would not be meaningfully engaged.

From this assertion, we also understand that the big ideas that were highly prevalent within students’ projects and designs were directly relevant to the science content covered within their physics class. While our observations did not note student opportunity or engagement with algorithms, the teachers argued that algorithmic thinking was embedded within student projects. While Mr. Volta asserts that algorithms are not “fun” for students, he then notes that the code they developed had algorithms within it and that mathematics is central to their scientific efforts within the class. This led us to further analyze the data to determine if participating students demonstrated Wing’s computational thinking practices within their physics inquiry projects. By examining whether Wing’s, (2006) pillars of CT mapped onto existing valued practices for science and engineering as laid out in the NGSS, we hoped to understand further not simply if students had opportunities to engage with overlapping science and computing practices, but we hoped to explicate what those behaviors might look like during a science inquiry project.

While many of Wing’s practices of computational thinking overlap with multiple related NGSS articulated science practices, Table 3 lists only those directly observed in our data.

As expected, the CT practices aligning most closely with the NGSS practices received the most attention and engagement from teachers and students alike. Of particular interest was how many practices within science and computing overlapped in common ways. For example, the computational thinking practice of abstraction and the NGSS practice of engaging in an argument from evidence both lent themselves to students’ engagement with models and simulations. Within students’ projects and inquiry, we saw youth collecting and using data for both their current idea as well as prospective future iterations. While there were nuanced differences between students’ goals, the skills and practices were common. This led us to wonder about how common reasoning skills and procedures were applied across STEM contexts for differing purposes and questions. If common skills were used to address differently lensed questions, then the cross-application of these skills and reasoning practices would lend themselves to deep integration and cross-application within the core content class with little additional needed time and effort on the part of the teacher. This led us to focus on our second research question.

RQ 2: In what ways, if any, can coding and computing be used to enhance instruction in physics classes?

| Big idea                                              | Student engagement | Example behavior                                                                 |
|-------------------------------------------------------|--------------------|----------------------------------------------------------------------------------|
| Computing is a creative human activity                | All                | Students created code to answer questions in collaborative groups                 |
| Abstraction reduces information and detail to focus on | All                | Students engaged in decision making about what facets of the physics to measure to answer their question |
| concepts relevant to understanding and solving problems|                    |                                                                                  |
| Data and information facilitate the creation of knowledge | Near All          | Students tested their hypotheses and collected their data to analyze              |
| Algorithms are tools for developing and expressing     | None               | N/A                                                                              |
| solutions to computational problems                   |                    |                                                                                  |
| Programming is a creative process that produces        | All                | Students build and coded accelerometer t-shirts to collect data                   |
| computational artifacts                                |                    |                                                                                  |
| Digital devices, systems, and the networks that        | Near All           | Students designed solutions to novel problems through integration of circuits, computing and wearable tech |
| interconnect them enable and foster computational      |                    |                                                                                  |
| approaches to solving problems                        |                    |                                                                                  |
| Computing enables innovation in other fields, including | Some               | Students mapped electric potential difference and then used code to explain the physics |
| science, social science, humanities, arts, medicine,    |                    |                                                                                  |
| engineering, and business                            |                    |                                                                                  |

Table 2 Frequency of presence of Grover & Pea’s “Big Ideas” of computing for students
We inquired of the teachers about their perspectives on when computing was most beneficial for students in their physics classes. Mr. Volta echoed his earlier answer and stated, “like I said, when the code explains the science or makes it so we can do the science better, that is when I want to use it.” This rooting in science content was an essential aspect of how and when teachers chose to engage with coding within their physics classes. Mr. Kirchhoff followed up on Mr. Volta’s comment and noted:

I love teaching these projects with the coding. So much of physics is solving the equations, which is important but kinda takes over for the kids. A lot of my kids don’t love the math side of it. I think that is why so many drop out in the fall. But this [the coding project] doesn’t focus on the math. These projects and the computing let my kids who don’t shine with calculus shine. Everyone can code this if they want to. Sometimes there are kids who don’t like coding, but this year a lot more kids said they like coding with the [e-textiles] projects than ever. I think the sewing makes it artistic. So it does not matter—they can be a good science student, a good programmer, or a good artist; any one of those kids can do this and love it. The code can explain the physics at the same time it lets them think for themselves.

This quotation packs in a lot of important affordances of coding within physics classes. Most notably, Mr. Kirchhoff’s comment elucidates a unique affordance in allowing new kids to shine in physics class. As he observed, coding lessened the load on kids, which enabled them to focus on calculus within their physics learning. In doing so, these projects allowed students who did not typically feel success in physics to feel that “shine.”

To further unpack each of the affordances for physics of the computational thinking practices observed, we analyzed our data sources for rich examples of the practices to explicate the students’ engagement with them. In order to understand the affordances of integrated physics and computing learning, we asked driving evidentiary questions designed to explicate student actions associated with engaging integrated physics and computing. In other words, around each CT practice, we asked questions specific to what we would expect students to do in evidencing a specific CT practice within a physics setting. With these questions in mind, we moved forward in examining our data for evidence of these practices as well as counter evidence of students unable or not afforded opportunities to engage these practices.

**Abstractions and Pattern Generalizations (Including Models and Simulations)**

In reflecting on abstraction and pattern generalization, we expected students to be able to operationalize those broader practices into specific actions that would be observed. In
our analysis, we asked ourselves “Can students work with incomplete information? Can students ignore information they deem unimportant to their goal?” The answers to those questions, we felt, would represent the specific actions and behaviors relevant to physics education that were tacit to this computational thinking practice.

While engaged in the Roller Coaster Myth Buster (RCMB) unit, students engaged in the practices of abstraction and generalization. Specifically, students’ t-shirt projects served to act as a visualized model of the gravitational forces associated with motion. Students discussed their experiences on roller coasters and cars, noting “it’s that feeling in your stomach going downhill in the car. It always happens to me. What does that feeling mean?” Students took embodied experiences from their daily life and extrapolated from them to discuss the scientific physical forces at play. Each student built his or her own t-shirt to meaningfully measure gravitational force on the ride of their choosing in accordance with abstract models of the physical mechanics.

Further, students engaged in abstraction when they needed to modify their teacher’s existing project to one that met the constraints of the specific ride they had chosen to examine. While the teacher designed and prototyped a working coded model for measuring g-force on a traditional roller coaster, the students generated abstractions of this example to then customize their own instantiations for two different coded projects that looked at measuring the forces at play on other types of rides. One of those rides was a slingshot style roller coaster which shot students straight up in the air and straight down again. Students learned through this process that while they wanted to measure only the upward g-force, the original design measured both the force going upwards as well as the counterforce, which led to rich discussions among students. One student noted:

This is getting tricky. So we were only thinking about the force going up, but there’s the force of gravity bringing us back down. How do we measure those forces? What do we call them? Now I have to find out how to code something that is the same but the opposite of what I am trying to measure.

Students then used their chairs to try to isolate the changes in forces by jumping up off chairs and then simply jumping straight off of them. The teacher required them to continue the experimentation process until they were able to articulate the physics at play and conceptualize a way to code the accelerometer to record the desired data (i.e., an abstraction of the phenomenon to be modeled). Students also recognized the accelerometers measure acceleration values nearing 9.8 m/s² when standing still, and that this value can be commonly categorized in a gravitational force equivalent, or g-force, rating as 1 g. Students used this understanding to also further build and test code that would light up LEDs in multiples of g-force values experienced. This meant they also needed to incorporate some mathematical algorithms in their code to compute various g-forces from the accelerometer’s acceleration values. As visible in Fig. 1, the lights on the microprocessor, being used as an external visual of force, change from on when the student is standing still to off when the student achieves the coded threshold of force by jumping.

**Systematic Processing of Information**

In reflecting on systematic processing of information, we expected students to be able to operationalize this broader practice into specific observable actions. We asked ourselves “Can students engage large swaths of data or information in a meaningful and reasoned way? Do they engage a process and/or tools when they attempt to work with data?”

When answering the questions around roller coaster myths, the students needed to collect, process, and analyze a great deal of data. Figure 2 shows a small portion of the data collected from each student’s t-shirt during RCMB Day. Students were required to use the data to analyze and evaluate safety information presented by the roller coaster company. The process of collecting approximately 200 data points from all the students, processing the data into a spreadsheet file, and then analyzing it demonstrates a staged and sequenced process for engaging with data for the purpose of gaining insight into the answers being sought. One example of this analysis is shown in Fig. 3, where a student writes up his hypotheses, the conditions of his analysis, and findings summarized with a p value.

**Symbol Systems and Representations**

In making sense of the CT practices around symbol systems and representations, we wondered what specific actions might be expected of students while they engaged in it. In thinking about the actions we would expect to observe, we asked ourselves “Are students able to use and explain symbols in their work? Can they use different symbols for different purposes?” Doing so would indicate strong student engagement with this computational thinking practice.

One of the greatest challenges of this integrated curricular approach was helping students move through multiple symbolic literacies at one time. On the one hand, students needed to engage in the learning and use of physics’ symbolic language. They also needed to engage with the syntax of coding, which created a challenging new literacy for students to learn. Engaging with these multiple representations of ideas presented interesting challenges for students as they attempted to navigate between the two. Students were observed relying heavily on commenting of the code.
to both engage the physics language and the coding syntax in a cognitively manageable and meaningful way. Figure 4 shows students engaging with commented code worksheets and their physics notes. Students were observed discussing the physics equations as part of their attempts to refine the code itself.

Because of the nature of e-textiles projects, students engaged multiple symbols and symbol systems at once. They worked with schematic drawings of the circuit design, which symbolically depicted aspects of the circuit, such as polarity. Even the use of LED lights as visualizations of g-force required students to think and talk about force symbolically. One student’s explanation noted “so each light represents a half g. If they all light up, we have the amount of force the ride says it has.” While the complexity and scaffolding of each of the various symbols differed, the use of symbols was evidenced through both the computing and science aspects of the project.

Algorithmic Notions of Flow of Control

As we engaged in analysis around algorithmic notions of flow control, we understood this process to require students to understand the procedural logic undergirding algorithmic thinking. To that end, we asked “can students design solutions that use logic and ordered steps?”.

We did not observe explicit information or indications that students were afforded opportunities to engage in this practice explicitly. As the teachers stated directly, they avoided using language about algorithms because of a belief that math was less fun for the students and would detract from student engagement and enjoyment of these projects. However, it is worth noting that when considered from the broader perspective of algorithmic thinking as a process of sequential problem solving and representing those processes in code using variables, students were afforded
several opportunities to engage this practice. As noted earlier with the student inquiries into the slingshot ride, students encountered the unexpected problem of accounting for rebound forces in their model and in their code. To resolve this, students engaged in a step-by-step process of problem identification followed up with solution development. This indicates that while teachers did not want to engage algorithmic concepts or language directly, the process of building working computational circuits necessitated students engage similar processes.

Structured Problem Decomposition (Modularizing)

In reflecting on decomposition, we wondered “can students break problems down into smaller, more manageable units?” If so, this would be evidence of decomposition from structured spaces and problems.

Because students were allowed to identify their own areas of interest to pursue within the constraints of the RCMB day activity, several opportunities for structured problem decomposition presented themselves. The e-textiles projects forced students to break problems into specific components in order to design solutions for them. Because an e-textiles project can fail in three ways (i.e., coding, construction, and/or design), makers of these projects need to be able to design solution testing processes that discretely identify the specific types of problems they encounter. With this practice, we focus specifically on the practice of deconstructing a problem, not the solving of the problem; we delineate debugging as the systematized process of solving those problems. Within this project, students demonstrated extensive problem decomposition as they sorted out the ways in which various considerations and constraints impacted their design. An example of this process of problem decomposition was heard when two students discussed a problem:

Fig. 2  Data collected and processed
Jill: It won’t work.
Louise: Why not?
Jill: I don’t know. It just won’t work.
Louise: Let me see. Mr. V says to check the big three before asking so is it the sewing?
Jill: What? How do I know?
Louise: Remember? ‘Check these three before you ask me.’ Remember? He told us it is usually one of three problems- the sewing, the coding, or an error of design.

The teacher taught students to break down problems into three categories that would identify likely issues. When asked about his instruction on problem identification, the teacher commented, “It is good if they have categories of problems to try and solve.” By categorizing problem types, students can deconstruct their projects into subsystems, identify underlying malfunction causes, and generate effective solutions more efficiently.

Iterative, Recursive, and Parallel Thinking

As we made sense of how students might operationalize iterative, recursive, and parallel thinking we asked “can students adapt their plan for newly received information or feedback? Can students use multiple information sources or systems to work on a problem?”

As part of the process of designing computational circuits with an intended purpose, students needed to process a lot of information and address issues systematically. Students needed to process information about the esthetic design of their project in conjunction with its functional needs and constraints. The design, construction, coding, and debugging process of e-textiles projects creates a strong opportunity for students to engage in parallel thinking and problem solving. As one student noted:

I really wanted mine to be an accurate picture of a heart. But I didn’t want any threads visible. So I had to make
a lot of choices about my design like resewing every thread with a matching color. Then I wanted my code to make it so it looked like my heart pulsed; I didn’t figure that out before Roller Coaster Day, but I am going to work on it this summer.

In her project, showcased in Fig. 5, we see the detailed effort to fuse the design goals with the data collection constraints and her efforts to code her project. The purple lights on her microprocessor became a coding challenge, since she only wanted the red lights to engage as this met her esthetic goals.

Conditional Logic/Efficiency and Performance Constraints

In reflecting on how students might operationalize and evidence conditional logic, we asked “can students evaluate their solutions and seek better ones based on novel information? Do they work toward optimizing their solutions and designs?” Doing so would mean that students had ample opportunity to engage in conditional logic.

Working to resolve issues and debug their code, students frequently talked through the conditionals present in the code they used for their project. For example, Fig. 6 shows two students debugging the code for their projects and
discussing the appropriate structure of a conditional. These conversations showcase the breadth and depth of the opportunities afforded students for engaging CT through e-textiles in the physics classroom.

**Debugging and Systematic Error Detection**

If students engaged in discourse around debugging, we felt that this would be strong evidence of systematic error detection. We searched the data for evidence that spoke to the question “can students solve problems that arrive in situ of their design? Do students engage problems through sequenced checking processes?”.

As noted earlier under the practice of structured problem decomposition, the e-textiles t-shirt affords students rich and complex opportunities to debug their work. Because of the multiplicity of options for potential problems with e-textiles computational circuits, students spend a great deal of time debugging circuits. One such issue arose with a student’s t-shirt that switched the lights based on the angle she was leaning at. As she debugged the issue with her teacher, this conversation occurred.

Teacher: SO when you tilt… tilt more. Tilt all the way back and all the way forward. Ok. Stand straight up.
Student: It is really picky about how I stand.
Teacher: Huh. I wonder why it does that.
Student: So it switches direction?
Teacher: Very cool.

Another conversation with a different student showcased a similar need for debugging projects:

Teacher: So what is it doing?
Student: I don’t know.
Teacher: Well, it says it is going to go on when it is tilted.
Student: Yeah.
Teacher: So it should be on right now?
Student: ummmm.
Teacher: Look, they went on!
Student: Yay!
Teacher: Wait, what is on pin nine?
Student: The vibe motor.
Teacher: Oh, so they [the lights] are all on pin 10?
Student: Yeah.
Teacher; Ok, that worked.

The debugging and making processes also helped students understanding of the science they were engaged in learning. As one student shared:

I like science a lot, but a lot of abstract concepts are harder for me to understand. So when I am making some-
thing, and it is being demonstrated in front of me, and I am actively making it happen and understanding it by doing it, I think that helps me a lot. Sometimes I won’t understand—like with the lights, I don’t remember where positive and negative go, but then it’s good that there is that challenge, because it is good we are doing this in this way, because the challenges I can easily figure out—because I can turn the light bulb around. I really did not understand electricity at all. It was always something I was really curious about, because I was like ‘how do lights work?’ and now I can go ‘oh circuits right and electrons,’ because now I am seeing these circuits being made, and I am making my own and I can see what is going on. I feel like I understand it a lot better.

Discussion

Prior research articulates specific barriers to classroom teacher integration of computing. Within science classrooms, teachers require increased content knowledge across computing and science content in order to effectively integrate them (Aldunate & Nussbaum, 2013; Ertmer et al., 2012). Without sufficient content knowledge in both areas, teachers are not able to engage the simultaneous instructional needs for integrated learning. Furthermore, even when teachers have the required content knowledge bases, they require professional models that make the practices and pedagogical strategies of integrated instruction and learning visible (Repencing, 2012; Smolin & Lawless, 2007). Within the curriculum and professional development, both of these known barriers were designed to scaffold. Because of that, Mr. Volta and Mr. Kirchhoff were successful enough in their teaching to branch out and layer in an additional level of complexity—an inquiry-based project that allowed students to engage in simultaneous physics and computing learning. The success of the project was evident in student responses and work product. However, the question remains of what implications exist for science teacher education.

Our science teachers were explicit in stating their belief that computing was only of value if it met their content area instruction goals. Importantly, to arrive at this belief, both teachers needed disciplinary knowledge in science and computing, a model curriculum to build from, and repeated professional development opportunities. For many practicing science teachers who have recently transitioned to the NGSS, computational thinking and other disciplinary practices are new. Thus, professional development can play an important role in supporting teachers in integrating computational thinking into the physics classroom and other science and engineering contexts. By creating scaffolded professional learning opportunities and materials, professional development providers can support experienced teachers into developing and practicing the needed pedagogical skills to integrate computing and computational thinking into their daily instructional practice.

With the evident value of developing integrated science and computing classroom opportunities, pre-service secondary science teachers can and should be provided with opportunities to engage in similar experiences as part of their methods courses. We are not suggesting that all pre-service teachers take computer science classes, as we know that there is already a long waitlist for these courses, but pre-service secondary science teachers should be asked to engage in computational thinking and other disciplinary practices. Furthermore, methods courses should provide models and examples of integrated learning opportunities that allow preservice teachers to engage in these types of integrative activities as they develop their pedagogical expertise.

Although the NGSS articulates “computational thinking” as part of its practices in a general statement, it does not make clear which discrete behaviors teachers should be implementing to facilitate its enactment. Further adding to the challenge of mapping CT and science inquiry, discussions of CT in the literature often list out discrete elements (e.g., abstraction, debugging, etc.); yet during authentic inquiry, they frequently co-occur in practice as students grapple with multifaceted problems. The findings presented here offer structured examples of how CT can manifest during specific standards-linked science activities. We see in the data robust evidence of the overlap of scientific reasoning skills as laid out in the NGSS and the computational thinking practices noted by Wing (2006). Further, we see evidence of student engagement in the big ideas of computing (Grover & Pea, 2013) across all facets of the student inquiry process. The mapping of these CT ideas to NGSS standards can be used as a starting place for guiding pre- and in-service teachers. It is not sufficient to merely introduce the big ideas of CT, for instance. Teachers must have opportunities to engage them and understand how the concepts come together when solving a problem.

Integrating computing into core curricular content can provide meaningful and worthwhile learning opportunities for students. E-textiles offer strong affordances for students to engage in multiple practices of CT and scientific reasoning simultaneously. Further, this study provided an opportunity to map discrete aspects of CT onto specific practices and behaviors associated with standards-aligned science instruction. As a specific medium, e-textiles offered multiple affordances to support these modes of thinking, as well as to engage students’ creative interests. When students engage in designing, constructing, coding, and debugging e-textiles projects, they engage in an intellectual challenge not typical to the K-12 classroom. Students must establish the root of problems be they construction and circuitry...
problems, design problems, or coding problems. Once the difficulty is actually identified, then they must set about fixing it. This creates a rich problem solving structure that, when integrated with inquiry settings, allows students to make meaningful connections across contexts. When students work with conventional electronics and computing materials, they are typically constrained to assembling pre-designed instruments. However, with the added creativity available to students through both the functional construction and esthetic design of e-textiles, students benefit from a greater degree of autonomy. Further, the required modification of code from an example facilitated independent CT and scientific reasoning as they coordinated the design of both code and e-textile artifact to meet the demands of their research questions.

This case study presents rich examples of how the valuable components of CT, design, and scientific inquiry can converge to afford students engaging and productive learning experiences. However, its key limitation is the manifestation of these interactions within a discrete project. Further research is necessary to identify underlying principles that can guide teachers’ direct facilitation of CT in standards-based science inquiry contexts. Furthermore, understanding and articulating the specific and discrete differences between scientific reasoning practices and computational thinking practices would better inform teacher classroom practice. As evidenced in our findings, a great deal of overlap between these two thinking practices exists and thus more evidence is needed to understand the ways they differ and what those differences would look like in practice and action by teachers and students. The development of such an articulation would create actionable guidelines that can be reliably and effectively implemented in classrooms will enable the CT and design opportunities illustrated here to become commonplace aspects of science education.

Declarations

Ethics Approval Approval was obtained from the ethics committee of Utah State University. The procedures used in this study adhere to the tenets of the Declaration of Helsinki.

Consent to Participate Informed consent was obtained from all individual participants included in the study.

Conflict of Interest The authors declare no conflict of interest.

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References

Aldunate, R., & Nussbaum, M. (2013). Teacher adoption of technology. Computers in Human Behavior, 29, 519–524.

Anderson, J. R. (1993). Problem solving and learning. American Psychologist, 48(1), 35.

Bass, E., & De Jong, D. (2020). Computer science courses as a graduation requirement at the state and national level: A policy brief. Tecumseh, MI: International Council of Professors of Educational Leadership.

Beane, J. A. (1995). Curriculum integration and the disciplines of knowledge. The Phi Delta Kappan, 76(8), 616–622.

Bell, T., Uhrahne, D., Schanze, S., & Ploetzner, R. (2010). Collaborative inquiry learning: Models, tools, and challenges. International Journal of Science Education, 32(3), 349–377.

Buechley, L. (2013). Thinking about making. Keynote. http://edstream.stanford.edu/VideoPlay/883b61dd951d4d3f00abeec65ead2911d

Bingimlas, K. A. (2009). Barriers to the successful integration of ICT in teaching and learning environments: A review of the literature. Eurasia Journal of Mathematics, Science & Technology Education, 5, 235–245.

Braund, M., & Reiss, M. (2006). Towards a more authentic science curriculum: The contribution of out-of-school learning. International Journal of Science Education, 28(12), 1373–1388.

Brennan, K., & Resnick, M. (2012, April). New frameworks for studying and assessing the development of computational thinking. In Proceedings of the 2012 annual meeting of the American educational research association. Vancouver, Canada I, p 25.

Capps, D. K., Crawford, B. A., & Constas, M. A. (2012). A review of empirical literature on inquiry professional development: Alignment with best practices and a critique of findings. Journal of Research in Science Teaching, 23, 291–318.

Cohen, J. (1988). Statistical power analysis for the behavioral sciences. Hillsdale, NJ: Lawrence Erlbaum.

Dougherty, D. (2013). The maker mindset. In Design, make, play (pp. 7–11). Routledge.

Eilam, B., & Yarden, A. (2007). Learning with a unified curriculum: science students’ knowledge organisation and cognitive flexibility. Curriculum and Teaching, 22(2), 5–27.

Ertmer, P. A., Ottenbreit-Leftwich, A. T., Sadik, O., Sendurur, E., & Sendurur, P. (2012). Teacher beliefs and technology integration practices: A critical relationship. Computers & Education, 59, 423–435.

Grover, S., & Pea, R. (2013). Computational thinking in K-12: A review of the state of the field. Educational Researcher, 42, 38–43.

Hartzler, D. S. (2000). A meta-analysis of studies conducted on integrated curriculum programs and their effects on student achievement. Unpublished doctoral dissertation. Indiana University, Bloomington.

Howell, J., Tofel-Grehl, C., Fields, D. A., & Ducamp, G. J. (2016). E-textiles to teach electricity: An experiential, aesthetic, hand-crafted approach to science. In C. Williams (Ed.), Teacher Pioneers: Visions from the Edge of the Map (pp. 232–245). ETC Press.

Huntley, C. (2010). Transforming education: Preparing teachers for the 21st century. Oklahoma Reader.

Fields, D. A., Searle, K. A., Kafai, Y. B., & Min, H. S. (2012, February). Debuggems to assess student learning in e-textiles. In Proceedings of the 43rd ACM technical symposium on Computer Science Education (pp. 699–699).
Krajcik, J., & Merritt, J. (2012). Engaging students in scientific practices: What does constructing and revising models look like in the classroom? Understanding a framework for K–12 science education. *Science and Children, 49*(7), 10–13.

Kreijns, K., Van Acker, F., Vermeulen, M., & van Buuren, H. (2013). What stimulates teachers to integrate ICT in their pedagogical practices? The use of digital learning materials in education. *Computers in Human Behavior, 29*, 217–225.

Lawless, K., & Pellegrino, J. (2007). Professional development in integrating technology into teaching and learning: Knowns, unknowns, and ways to pursue better questions and answers. (2007). *Review of Educational Research, 77*, 575–614.

Lederman, J. S., Lederman, N. G., Bartos, S. A., Bartels, S. L., Meyer, A. A., & Schwartz, R. S. (2014). Meaningful assessment of learners’ understandings about scientific inquiry—The views about scientific inquiry (VASI) questionnaire. *Journal of Research in Science Teaching, 51*, 65–83.

Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic inquiry*. Sage.

Makki, T. W., O’Neal, L. J., Cotten, S. R., & Rikard, R. V. (2018). When first-order barriers are high: A comparison of second- and third-order barriers to classroom computing integration. *Computers & Education, 120*, 90–97.

Majoni, C. (2017). Curriculum overload and its impact on teacher effectiveness in primary schools. *European Journal of Education Studies*.

McGaffrey, D. F., Hamilton, L. S., Stecher, B. M., Klein, S. P., Bugliari, D., & Robyn, A. (2001). Interactions among instructional practices, curriculum, and student achievement: The case of standards-based high school mathematics. *Journal for Research in Mathematics Education, 32*(5), 493–517.

Nager, A., & Atkinson, R. K. (2016). The case for improving U.S. computer science education. Washington, DC: Information Technology & Innovation Foundation.

National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. National Academy Press.

Nelson, B. C. (2007). Exploring the use of individualized, reflective guidance in an educational multi-user virtual environment. *Journal of Science Education and Technology, 16*(1), 83–97.

Penuel, W. R., Fishman, B. J., Yamaguchi, R., & Gallagher, L. (2007). What makes professional development effective? Strategies that foster curriculum implementation. *American Educational Research Journal, 44*, 921–958.

Peppler, K., & Glosson, D. (2013). Stitching circuits: Learning about circuitry through e-textile materials. *Journal of Science Education and Technology, 22*(5), 751–763.

Repenu, A. (2012). Programming goes back to school. *Communications of the ACM, 55*(5), 38–40.

Smolin, L., & Lawless, K. (2007). Technologies in schools: Stimulating a dialogue. *Yearbook of the National Society for the Study of Education, 106*(2), 1–10.

Stephenson, C. (2015). The thorny issue of CS teacher certification. Google for Education. Available at http://googleforeducation.blogspot.com/2015/07/the-thorny-issue-of-cs-teacher.html

Tofel-Grehl, C., Fields, D., Searle, K., Maahs-Fladung, C., Feldon, D., Gu, G., & Sun, C. (2017). Electrifying engagement in middle school computer science class: improving student interest through e-textiles. *Journal of Science Education and Technology, 1*, 1–12.

Tofel-Grehl, C., Jex, E., Searle, K., Ball, D. & Zhao, X. (2020). Electrifying: One teacher’s discursive and instructional changes through engagement in making to teach science content. *Contemporary Issues in Technology and Teacher Education*.

Vars, G. F., & Beane, J. A. (2000). Integrative curriculum in a standards-based world. ERIC Digest.

von Secker, C. E., & Lissitz, R. W. (1999). Estimating the impact of instructional practices on student achievement in science. *Journal of Research in Science Teaching, 36*, 1110–1126.

Windschitl, M. (2003). Inquiry projects in science teacher education: What can investigative experiences reveal about teacher thinking and eventual classroom practice? *Science Education, 87*(1), 112–143.

Windschitl, M., Thompson, J., & Braaten, M. (2008). How novice science teachers appropriate epistemic discourses around model-based inquiry for use in classrooms. *Cognition and Instruction*, 26(3), 310–378.

Wing, J. (2006). Computational thinking. *Communications of the ACM, 49*, 33–35.

Zohar, A., & Nemet, F. (2002). Fostering students’ knowledge and arguments skills through dilemmas in human genetics. *Journal of Research in Science Teaching, 39*(1), 35–6.

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