Creating a computational playground in high school physics

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The competencies required of physics-oriented STEM professionals are rapidly evolving to include computational practices (the use of computers to study physical systems). Developing these practices in students requires sustained learning experiences, and high school students benefit from encountering this domain at an appropriate level. However, many high school physics teachers have had limited (if any) exposure to computation, let alone practice with integrating it at the high school level. Our interdisciplinary team of university STEM educators designed and facilitated two semesters of an online professional development sequence on computational integration for high school teachers. This sequence included asynchronous modules and monthly remote meetings centered around teachers reflecting on their experiences as learners and adaptations to these modules for delivery in their classrooms. At the end of spring 2022, we conducted semi-structured interviews to explore the teachers' experiences and plans for implementation. When analyzing the transcripts from the remote meetings and interviews, we attended to how the teachers operated within two frames. The *learner frame* focuses on what the teacher is learning about computation, what piques their own curiosity and interest, and what they feel they can accomplish. The *mediator frame* focuses on what they believe their students could reasonably accomplish with computation, what their students are curious about, and how they can use computation to develop their ideal classroom environment. Our analysis highlights these teachers' enthusiasm about how computation can contribute to the playful, creative environment that they value in their classrooms. They also perceived that curiosity was a necessity for productive computational integration and that computation could engage students' curiosity in new ways. We offer implications for future iterations of professional development to emphasize computation's potential to inspire curiosity in all students.

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I. WHY COMPUTATION IN HIGH SCHOOL?

In order for computational thinking to be effectively introduced to students as an interdisciplinary practice of using computers to understand STEM-related concepts [1–6], it must be integrated across disciplinary subjects [7, 8]. The physics education community has taken up this charge [9, 10] by creating activities that develop computational thinking in a physics context [6, 11, 12] and that use computation to further develop students' conceptual understanding of physics [13–16]. While significant progress has been made in integrating computation into the undergraduate physics experience [17], the high school context has seen much less development.

Orban and Teeling-Smith [7] make a series of cogent arguments for the value of computation in the high school physics context. Integrating computation provides a more complete picture of what physics is like, and computation itself adds another representation of physics to a student's toolkit. Simulating a physical system introduces new challenges that develop a valuable skill set. Furthermore, developing computational models increases the intellectual diversity of the physics learning experience with novel prompts for sense-making. These arguments overlap significantly with more universal framings of computational thinking practices in STEM education (e.g., simulation, modeling, handling data, gaining insight, and systems thinking) [3]. Computation therefore adds another venue for engaging in practices that are already part of the physics curriculum [2, 6, 18, 19].

Although pedagogical and technological innovations in computationally integrated physics education are emerging, high school teachers may have limited experience with current programming languages and freely-available computing platforms. Consider, for example, a mid-career high school physics teacher who graduated in 2000 with only a single programming course in an older programming language like FORTRAN. They are likely to feel excitement at the prospect of integrating computation into their course while also feeling trepidation at learning a newer programming language (such as Python) in a new environment (such as a Jupyter notebook hosted on a web site). High school physics teachers are unlikely to have peers with computational integration experience within their schools. This need can be addressed by creating active learning communities that provide resources and ongoing support to build and sustain computational integration in high school physics classrooms [20].

In this paper, we explore this dynamic in the context of a series of self-paced online professional development (PD) modules created by university STEM educators to prepare high school physics teachers to integrate computation into their classes. Building on recommendations for PD design that connects learning experiences to classroom practice [20, 21], we designed these modules for teachers to experience computationally integrated content as learners, to reflect on how they might adapt these materials for adoption in their classrooms, and to explore pedagogical and logistical needs for implementation. We endeavored to create a professional learning community through monthly remote meetings interspersed with asynchronous communication for answering questions and troubleshooting technology. As our participant teachers pivot from PD learning to planning for classroom implementation, we are interested in the question, "How do teachers' beliefs about students and learning environment relate to their readiness to integrate computation in high school physics classrooms?" We examine their beliefs about productive physics learning environments and the motivations of their students within the context of this collaborative PD. We seek to better understand how these beliefs connect to the likelihood that the teachers will follow through and sustain classroom implementation after the PD has concluded.

II. PROFESSIONAL DEVELOPMENT CONTEXT

Our PD program consisted of two tracks: a general computational integration track and a quantum-focused track. Both tracks presented material in a series of Jupyter notebooks [22] hosted on Google Colab [23] that teachers could complete at their own pace and adapt for use in their classrooms. The general computational integration track included activities about importing and manipulating lab data, simulating motion using the Euler-Cromer algorithm, and creating visualizations of electric fields. These topics were chosen to provide a basis for activities a high school physics teacher could use throughout the school year. The quantum-focused track used a spins-first curriculum [24–26] and Python arrays [27] to reduce the mathematical demands of learning quantum concepts such as probability, measurement, and expectation values. Teachers could choose to complete one or both tracks.

We conducted this PD for one cohort during fall 2021 and a second cohort during spring 2022. Teachers completed one instructional module per month with monthly on-line meetings to review progress, answer questions, and reflect on potential classroom implementation. Although advertisements for the PD program were well received and generated interest from over 20 teachers, only 2 teachers in fall 2021 and 1 teacher in spring 2022 completed both tracks. The qualitative findings in this paper are based on analysis of insights offered by the 3 teachers who completed both tracks.

1. **Drew** completed the quantum-focused track in fall 2021 and the general computation track in spring 2022. He identifies as White and male and has undergraduate degrees in physics and classical music. He had been teaching for 7 years, all at the same school.
2. **Javier** completed the quantum-focused track in fall 2021 and completed the general computation track in spring 2022. He identifies as Latino and male and has an undergraduate degree in physics with a concentration in astronomy. He had been teaching for 5 years, 4 in his current school and district. Javier and Drew teach in the same district.
3. **Tom** completed both tracks in spring 2022. He identifies as White and male and has undergraduate degrees

in physics and interdisciplinary studies with a minor in astrophysics. He had been teaching for 3 years, all at the same school.

While this sample is limited in size and diversity, we find the insights offered by these teachers helpful in understanding the impacts of the PD program and in making revisions for future iterations.

III. CONCEPTUAL FRAMEWORK & METHODOLOGY

In this study, we consider how high school physics teachers approach PD and implementation through two different frames. A frame is an internal structure of expectations one uses to make sense of a learning experience [28–30], answering the question, "What is it that's going on here?" A frame determines what previously developed knowledge and practices one is likely to activate while learning new knowledge and practices [31–33]. Framing is important in teacher PD, as it emphasizes how teachers' prior experiences shape their ideas and values about student learning [34, 35].

We consider two related but distinct frames a high school physics teacher might employ when integrating computation into their classes: a learner frame and a mediator frame. Their *learner frame* focuses on what the teacher is learning about computation in the process, what piques their own curiosity and interest, and what they feel they can accomplish. Their *mediator frame* focuses on what they believe their students could reasonably accomplish with computation, what their students are curious about, and how they can use computation to develop their ideal classroom environment. The interaction of their learner frame and their mediator frame helps us describe the transition from the teachers' experiences in the PD to their implementation of what they learned in the classroom.

We assessed these teachers' experiences in three ways: First, we conducted a survey of the teachers' demographic information and teaching backgrounds. Second, we recorded each monthly meeting with the teachers. Third, we conducted semi-structured interviews, prompting teachers to reflect on motivations for joining the PD program, learning experiences, classroom implementation (achieved or planned), and need for additional resources. The monthly meetings and interviews were recorded and transcribed using Zoom remote meeting software. We reviewed the recordings and transcripts for themes, with one author (Galanti) taking the first pass on the meetings and another (Lane) taking the first pass on the interviews. We then compared themes and identified overlap in our observations, grouped transcript excerpts based on theme, and counted the number of excerpts that illustrated each theme.

IV. FINDINGS AND DISCUSSION

Here we discuss the themes that occurred most frequently and that answer our question, "How do teachers' beliefs about students and learning environment relate to their readiness to integrate computation in high school physics classrooms?" We seek to understand how their experiences as physics learners in the PD context motivate their plans for classroom integration as physics facilitators. The themes that emerged in our analysis included the teachers' beliefs about what makes physics engaging, the teachers' beliefs about their students' interests and readiness to use computation, and the adaptations they found necessary for delivering computationally integrated instruction.

A. Beliefs about computation and high school physics

Many of the teachers' comments reveal beliefs they hold about what makes a productive high school physics experience. This belief system includes how they learn and what they enjoy learning (learner frame) and what their classroom should be like for their students to learn (mediator frame). We begin with observations of the teachers speaking from a learner frame.

Each teacher expressed personal engagement and interest in the material. For example, when asked, "What interactions or conversations were most helpful in the PD?" Javier said that he found "most of [the interactions] very stimulating. Each meeting I have learned something new. I found every time we've had discussions, I get excited about the implementation and I end up at the end of the meeting going and doing some research of my own of using the materials." We note here that both the PD materials and the collaborative meetings were necessary components of Javier's learning experience for him to further engage in this way. After completing the first module in both tracks, Tom described how he enjoyed re-learning computational practices and quantum concepts he had experienced as an undergraduate. "I've been having fun. It's nice to kind of get back into it." Both Tom and Drew contrasted this level of interest with less personal engagement with standard high school physics topics. Tom commented that "teaching the Physics 1 stuff is kind of nice but it's nice to actually get back into doing the things I loved doing at college," and Drew expressed that he "would like to be able to cover some more interesting topics." This rediscovered interest in computation calls back to the argument Orban and Teeling-Smith make about computation enhancing disciplinary authenticity in the physics learning experience [7].

Within a learner frame, the teachers also found the playful approach that the computational activities encouraged to be engaging. After completing the first module in the general computation track, Javier stated that he "started playing around with the numbers like a game where you don't really know the goal, or like the actual route that you would take." This comment speaks to one way in which computation enhances disciplinary authenticity [7]. He saw playfulness within the module design: "I think structure is important. If you can make it like a playground. I'm imagining a video game, where it's not quite the most intuitive thing but you are playing around, you're tweaking with numbers, you're coming to conclusions. You can restart and try again." We note that in none of these comments do the teachers explicitly reference their students. They are describing their own positive experiences with computationally integrated learning.

The teachers' descriptions of an ideal learning experience extended beyond computation and provided insight into how they operate within a mediator frame. After Javier discussed his own playful experience above, he further described how a playful environment promotes student independence: "It gives [the students] a little bit of independence and a little bit of autonomy." Implied in this statement is that this aspect of independence and autonomy was not available to students without computation. Reflecting on his first use of computation in the classroom, Tom similarly commented, "Some of [the students'] curiosity has brought some really interesting results. I like what they've done with that freedom. That gets everyone more comfortable to try out crazy things." These comments help us connect the learner frame ("I started playing around") to the mediator frame ("I like what they've done with that freedom"). Here, we see the teachers passing along freedom they have experienced as learners to their students.

We also see this connection between learner frame and mediator frame in how the teachers were enthusiastic about seeing their students express interests similar to theirs. For example, when asked, "What first motivated you to participate in the PD Program?" Drew commented, "I would like to be able to cover some more interesting topics for both myself and the students." This speaks to a personal motivation of interest that he can carry into his classroom. When Javier discussed his first classroom implementation of computation, he described collaborative facets of the learning experience [8] that the activities promoted beyond learning physics and computation: "They were discussing and communicating, comparing and contrasting each other's ideas. The buzz is what you want in the classroom. You want them to be joking around. I'm really excited. I think these are going to elevate that dynamic to another level. It's the essence of the scientific collaborative ideology. [It] keeps them from leaning on the one student who has all the answers."

B. Beliefs about their students

Within a mediator frame, the teachers indicated that their integration of computational practices and physics concepts would be based on their students' readiness and how these practices align with their curriculum. Here, we examine the beliefs about their students that guide this integration.

We find that the teachers base some of their expectations for student curiosity on their own interests, likely connected to their enthusiasm as mediators. For example, after Drew's earlier comment about wanting to cover more interesting topics, Drew commented that "[in my] very low level classes, I never get to talk about these types of concepts because it's just so complicated [without computation]." For Drew, introducing additional topics via computation is something he *gets to* do. Similarly, when asked how he saw computation fitting into his curriculum, Tom commented that "the computational activities still tie into the overall theme of physics and what we're doing but it gives them that little breath of fresh air so it's not always just the mechanics curriculum." He sees his students as needing the "fresh air" that computation can afford.

Comments about students' receptiveness to computational integration suggest that curiosity is a prerequisite for engaging in a computationally integrated curriculum. Teachers' statements that students who have previously demonstrated curiosity about physics or computing would benefit from this curriculum are noteworthy; one of the goals of the PD was to support teachers in broadening interest in STEM. For example, after Javier described his playful experience above, he noted that the appeal of computation for curious learners. "I found [the modules] very interesting and very intriguing. I can only imagine the students, especially the curious ones, are going to feel the same way." Similarly, early in the PD while discussing potential classroom implementation, Drew thought computation would disproportionately appeal to curious students, describing computation as "accessible for students that are naturally inquisitive. I have a few students that are like that, but a lot of them are not. I'm not sure how many of my students would be inquisitive enough to just jump in." We note that our interviews and meeting records contain no discussion of how computation might develop students' curiosity or interest, perhaps speaking to a motivation-related fixed mindset instead of a growth mindset [36]. As these teachers carry out their implementations, it will be interesting to observe how they view curiosity differently after computation has transformed the way they teach particular topics within their physics classes. They see the possibility that computation might appeal to student curiosity by making new topics accessible (i.e., quantum concepts). One month after his previous comment, Drew expressed optimism for computation as an entry point. "I don't know how much of the actual quantum I will be able to institute with my students. I'm interested to try, but I don't know how much of it they'll grab."

The teachers expect that their students will need scaffolding and support. After Drew implemented a few computational activities at the end of the school year, he described the need for such scaffolding to span the entire year: "If I could start implementation at the beginning of the year, that would make things a lot easier because I could get them doing some basic programming and then, as the year goes on, we could flesh that out more." Continuing his discussion of where to integrate computation in his course, Tom described a similar need: "It's not too much of an ask to incorporate [computation] little by little, weekly or biweekly throughout the entire year." When asked about potential challenges of implementation, Javier indicated a similar need for his AP class: "[In] my AP 1 and 2 class, it's difficult to implement in addition to all the material we're covering. I would have to do it from day one and do it consistently throughout the year so their learning curve isn't as steep." These teachers want to provide their students with foundational programming and technological knowledge to allow them to access the physics content.

When asked, "Is there any support that we can provide that you would need in order to implement the computational activities further?" Javier described a need for more opportunities for students to practice, saying he would need "worksheets or activities that students could do within the Jupyter notebook. It would be really helpful to give them some kind of lab or homework assignment to edit that code coming at this from a different angle." Drew expected to need to further break down the modules to a more granular size: "They're broken down pretty small now, two or three concepts, but I could see for my students even breaking it up more so." These statements imply that the teachers are not confident that their students share the same level of curiosity that sustained the teachers through the modules. The next subsection discusses how this difference informs their implementation plans.

C. From beliefs to action: Adapting for the classroom

By the end of April 2022, Tom and Javier had already begun implementing computational activities in their classroom. Their comments about implementation illustrated how the need for curiosity informed many of their implementation decisions. After completing the second module in both tracks, Tom described plans to introduce computation gradually to test out his students' curiosity: "I have some students that I've talked to about this, and so I think I'll share maybe one or two [activities] and see what they think, see if it's something that they get. Because I have some students who asked questions about even Modern Physics stuff." Additionally, after completing the PD, when asked, "What sort of adaptations would you like to make to the activities?" Tom expressed a need to engage student curiosity throughout the computational integration: "I think, as we do some of the mathy parts, if they can get like a small taste of an area where that's used, just add a little tidbit of, 'Why are we learning this part? Why are we doing this math? Where does this math click?' Kind of the reminder that, 'Yes, we're doing math review right now but it's to do science, it's to do physics.'" When asked to compare the potential excitement level of the modules, Javier expressed concern that some of the visualizations would not fully engage students: "[In the] spin modules we were dealing with bar graphs which were a bit less exciting." Again, these comments reveal a view of curiosity as prerequisite for engaging in computational activities.

The teachers have a very positive outlook toward what they can accomplish with computation in their classes. When Drew discussed his planned implementation, he said that computation has an additional affordance of encouraging students to reason more about graphing and relationships between quantities: "I'm interested to try to put in some of the data analysis and have them play around with the models and have them see the graphs because I think that's a place where my students are lacking." At the end of the PD, Tom reported already seeing positive student outcomes, describing students as "grateful that they got to do something before they graduated that was coding related. [They] feel a little more confident now and see that it's not all that bad." Javier was particularly interested in seeing what his IB students would accomplish using computation in their independent final projects: "They don't have to follow the conventional ways of solving this problem. It presents them with another tool that they can use to complete their own [final project]. Giving them that extra dimension allows them to have greater freedom to be creative." These teachers' beliefs about the affordances of computation are being actualized in their classrooms.

Both Drew and Javier were strategic in which classes they chose for their first implementation. Javier preferred to first integrate computation with his IB class rather than his AP class as "they generally seem to be more excited about learning the concepts, so they'll take more initiative." Again, we see an example of curiosity as a prerequisite rather than as a disposition to be developed. Drew felt more confident about integrating computation with his AP class than with his standard class. These comments reveal an assumption that student curiosity scales with the rigor of their physics class. Both teachers continue to encounter challenges with student access to computing platforms (e.g. Google Colab, Github) as they work toward full classroom implementation.

V. CONCLUSIONS AND NEXT STEPS

We have described our implementation of a PD program for high school physics teachers interested in integrating computation in their classes. We analyzed meeting and interview data to understand how their beliefs about students and classroom informed their implementation plans. The teachers' characterization of computational modules as creative physics tools was consistent with their ideas about playful, productive classrooms. Their plans for scaffolding implementation bridged their own curiosity and interest as physics learners and their beliefs about student readiness.

Their assumptions that the most curious or interested students would appreciate computation warrants further investigation as we strive to make physics more accessible to a broader population of students. These findings will also inform future iterations of PD module design and continuing support for teachers. We are particularly interested in conducting a more thorough assessment of the conceptual affordances of computation, particularly in relation to quantum concepts, in future classroom integration.

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