CENTERING STUDENTS' PERSPECTIVES IN COMPUTATION-INTEGRATED PHYSICS CURRICULA

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ABSTRACT

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Physics education researchers and curriculum developers have recognized the experiential expertise of students, using students' perspectives to make improvements to curriculum and pedagogy. Recently, they have given students more control in this process, sometimes even a direct voice in curricular decision-making. This dissertation intends to introduce and apply these student-centered research methods to a new type of curriculum: computation-integrated physics. Even though computational modeling is being integrated widely into physics curricula as a learning tool, there is no consensus on assessment, curriculum, or learning goals. This gap provides an opportunity to build an understanding of what matters to students in this new context from students' perspectives and make recommendations for curriculum and pedagogy.

Using a qualitative case study methodology, I present an in-depth view of how students perceive their experiences in these computation-integrated classrooms. In total, the dissertation spans four studies in two research contexts. The first study illustrates how case study can be used to center a student's perspective on her experience as an undergraduate learning assistant in a computation-integrated physics course. Building on the first study, the second study is a more in-depth case study on the cohort of learning assistants in the course, in effect demonstrating how students' perspectives can be translated into pedagogical expertise when examined with an attention to context and a grounding in a theoretical perspective. For the last two studies, I shifted the research context to a computation-integrated high school physics class. The third study is an exploration of students' accounts of the challenges they face when doing computational activities in their physics class, including those related to computation, the integration of computation with physics, and the contextual factors in the classroom. Using the students' perspectives once again, the fourth study uses a theoretical framework to characterize students' tendencies to engage productively with

computation. This final study demonstrates that examining students' perspectives with a theoretical basis and contextual attentiveness can provide a platform to step into student-centered curricular change in computation-integrated physics.

Overall, these research studies come together in this dissertation to show that paying attention to students' perspectives and affect in computation-integrated physics courses is key to understanding how to support students when teaching a computation-integrated curriculum. The findings also bring researchers and curriculum developers a few steps closer to infusing students' perspectives directly into curricular and pedagogical decisions in computation-integrated educational settings.

I dedicate this dissertation to Otto, Circe, Beck, Blaine, Joyce, and Ed.

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CHAPTER 1

INTRODUCTION

Students have a central role to play in how physics curricula continue to develop. Physics education researchers, curriculum designers, and teachers have used students' perspectives as insightful resources [9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23]; institutional science standards have aligned with student-centered approaches to schooling [24, 25, 26, 27], and students themselves have been handed more power to make physics classroom decisions [28, 29, 30, 31, 32]. Ultimately, this focus has led to calls to gain a deeper understanding of the experiences of physics students [33]. My aim in this dissertation is to show how physics students' perspectives can provide insight into possibilities for curricular change and further research into their experiences, especially in the context of computation-integrated physics.

There have been many efforts in a variety of contexts to incorporate the perspectives of students into curriculum design and pedagogy [29, 32, 34, 35]. These instances of students gaining control over institutional processes are often spurred on by research into what students and/or institutions stand to gain from redistributing power [28, 36, 8, 37, 38]. This dissertation aligns with such research efforts because each study provides a window into what students teach us about a learning environment and provides a pathway for how those findings could motivate student-centered curricular change.

One realm where curricula are changing significantly is physics classrooms through the integration of computation [39, 40]. Rather than being taught as a separate coding class, computational modeling is being integrated into physics curricula as a tool for learning science and representing physics concepts in new ways. In the last two decades, there has been serious consideration of curriculum redesign around computation [41, 42, 43, 26] with more widespread calls to incorporate computation in the last ten years [24, 27, 44], yet still no widespread agreement on assessment, curriculum, or learning goals. Due to the relative newness of computation in physics curriculum, little work has been done on what makes a computational-curricular integration effective for learning, motivation, and attitudes [33]. Because these constructs revolve around student affect, there is a need for incorporating students' perspectives into research on these new computation-based physics curricula.

The role I intend for this dissertation to play is to incorporate students' perspectives into computation-integrated physics curricula by studying and communicating what students have to say about their experiences in physics class with integrated computation. It is only by listening to students that we can begin to change the structure of teaching and learning in their favor. Historically, physics curriculum designers and researchers have attempted to incorporate student perspectives via understanding how students organize their content knowledge [9, 10, 13, 19, 18], view their learning [11, 14, 15, 17, 23], and view pedagogical strategies [12, 21, 20]. However, these efforts have not been extended into the context of a computation-integrated physics curriculum. Due to the changes a physics curriculum undergoes to incorporate computational modeling, we need research on how students experience this new learning tool and how its curricular use can be improved.

The research I present here is designed to provide an authentic, in-depth, rigorous view of how students perceive their experiences in these computation-integrated classrooms. In striving for authenticity, I base my work in the words of students themselves, mainly via semi-structured interviews [45] and recordings of students working in their natural classroom context. To provide depth, my work is qualitative, meaning I focus on social phenomena by studying its participants and taking detailed accounts of their interpretations. To ensure my work is rigorous, I use a widely accepted research methodology: qualitative case study [46, 47, 48, 49, 7, 50, 51, 52, 53, 54, 55, 56].

In summary, I am motivated by a need to center students and incorporate their voices into physics curricula. I explore this need first in a university context where student voices already have significant power in curriculum design (Chapters 4 and 5) and second in a high school context where the curriculum is new, changing, and ripe for student voices to shape it (Chapters 6 and 7). I use case study throughout the chapters to illustrate the richness that can be drawn from studying student perspectives in an in-depth, qualitative fashion. Below, I provide a roadmap with more details.

This dissertation is a presentation of four research studies in two contexts. Chapters 4 and 5 investigate the experiences of undergraduate learning assistants (LAs) in an introductory, computation-integrated physics course and their dynamic relationships with the curriculum that they teach. Chapters 6 and 7 are studies on students in a high school physics class into which computation has been newly integrated. I tie these chapters together by providing a background and literature review in Chapter 2, where I explore the background of research on physics LAs, computation, and the use of student perspectives in curriculum development. I also introduce some of the theories and models that help provide inroads to studying student perspectives in the relevant contexts.

In Chapter 3, I flesh out the methodology used in all my research studies: qualitative case study. Case study is ideal for researching a phenomenon in its natural setting via multiple data sources [47, 46]. My use of case study develops in complexity moving from Chapter 4 to Chapter 7. I begin with a generic case study, then transition to using more structured case study methodological choices. Because case study is used sporadically and with much variance in physics education research [57, 17, 23, 21, 22, 58, 20, 59, 13, 16, 19, 10, 18], I orient Chapter 3 to introducing qualitative case study and its traditions to an unfamiliar reader.

Chapter 4 is a published paper [60] on the case study of an LA for an introductory physics course. I use the study to illustrate an example of how case study and student perspectives join together constructively in a context where a student has a dynamic relationship with the course she teaches. In this case, the use of case study is the driving force behind centering the student's perspective, and the findings serve as a jumping off point for the next chapter.

Chapter 5 is an in-press paper [31] (accepted in Physical Review Physics Education Research). that expands on the research design from Chapter 4 to include the perspectives of other LAs and a faculty member. The focus of this chapter lies in how the expertise of LAs has been leveraged via the design of the course and via their relationships with faculty members. This chapter uses case study to center the interpretations of LAs and make an argument for how the impact that LAs have on the curriculum could be expanded and formalized. For the purposes of this dissertation, Chapter 5 is also a demonstration of the efficacy of using case study to investigate the relationships between a curriculum and the some of the students who interact with it.

Chapter 6 is a case study on high school student perceptions of the challenges they face in a computation-integrated physics class. This chapter serves as a demonstration of case study in a high school physics classroom setting. Unlike the LAs from Chapters 4 and 5, the participants in this study do not have much influence over the curriculum. Accordingly, much of my investigation focuses on describing the perspectives of these high school students and framing the findings as an opportunity to design computation-integrated curriculum with student perspectives in mind.

Chapter 7 is another case study on the students and context from Chapter 6. This study applies a framework originally theorized for analyzing a person's orientation towards learning computationally in a mathematics context called the Computational Thinking Dispositions framework [1]. I apply the framework to the perspectives of high school students in an effort to demonstrate the framework's efficacy in the context of computation-integrated classrooms and build a connection to the more established construct of mindset. This chapter demonstrates that a case study on student perspectives can provide motivation for student-centered curricular change in computation-integrated physics classrooms.

Chapter 8 is a discussion of the ideas I build and test throughout the dissertation. I review the uses and benefits of qualitative case study, the importance of researching students' perspectives, the limitations of this work, and the potential for such research to influence curriculum in ways that benefit students.

CHAPTER 2

LITERATURE REVIEW

This chapter is a literature review that provides context and motivation for the chapters that follow. I begin by reviewing how students' perspectives can be incorporated into curriculum design choices, and I describe the setup of Chapters 4 and 5 to show why it matters to listen to students. Then, I introduce a curricular context where students' perspectives need to be leveraged more: computation-integrated physics. In order to address this need, I lay a foundation of literature that calls attention to students' perspectives in computationally integrated physics, which aligns with the setup for Chapter 6. Lastly, I build on that foundation to set up the background of a study (Chapter 7) that uses students' perspectives to explore and apply a framework of student dispositions with the potential to offer improvements to curriculum in computation-integrated physics.

2.1 Incorporating students' perspectives into curriculum

My interest in using students' perspectives is grounded in the history of doing research on what students have to say about their physics learning and making corresponding suggestions for curricular improvements [9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 61]. The focuses of these studies are mostly qualitative and span from understanding how students organize their content knowledge [9, 10, 13, 19, 18] or view their learning [11, 14, 15, 17, 23] to how they view different pedagogical strategies or classroom supports and how students think those strategies and supports could be improved [12, 21, 20, 61]. In general, physics education researchers consult students' perspectives to catalog experiences from the perspectives of students and use those findings to think about potential improvements to curriculum and pedagogy. With this dissertation, I aim to contribute to this collective effort.

To understand how student perspectives can be leveraged more directly and more expansively in curriculum, I investigated a recent model for gathering and implementing student input called Students as Partners (SaP) [28]. This model allows students to engage with their instructors on course design. In SaP, students are viewed as experts on their own learning and use that expertise to help make decisions on curriculum and pedagogy for a course. There is a focus on partnership, which means students can be positioned as co-developers of curriculum through their collaborative relationships with faculty or some other curriculum developer. While it is possible that students can be enrolled in the course for which they are consulted, they do not need to be—in some cases the student-partners are employed as learning assistants (LAs) [30, 31]. Due to the relative recency of higher education's embrace [32], SaP has just begun to be used to describe instances where students have significant voice in curricular decisions in physics contexts [29, 31].

My use of SaP to describe a student-partnership in a physics context [31] was an expansion of an earlier study on the perspective of a student who helped teach introductory physics [60]. Chapters 4 and 5 represent the work from these two studies. I found in the first study that students had rich reflections on their experiences and deeply insightful thoughts about how a physics course could function [60]. This fed my interest in the value of listening to students about their experiences and leveraging what they say to make meaningful curricular changes. Eventually, this led to the second study, which expanded my focus to a handful of students who were employed as learning assistants (LAs) and had opportunities to infuse their perspective into the curriculum of the course they helped teach [31].

The main takeaway from doing this work was that it is not enough to just listen to what students have to say. There also needs to be a theoretical framework in place and a consideration of contextual features to help to interpret students' perspectives. Listening to students without structure to how their voices are incorporated into the curriculum can lead to reactionary instead of thoughtful changes. Context and theory are important for informing how student perspectives can be listened to and used as feedback to facilitate productive curricular change. For example, in Chapter 5, I used the SaP model [28] to describe the power undergraduate LAs held in curricular decisions. I also used the theory of Communities of Practice (CoP) [62] to help me describe how LAs can develop their expertise over time and make decisions that align with the goals of the community of LAs. I choose to use CoP to describe this phenomenon because the course itself was designed around that theory [63]. It also provided a mechanism for describing how LA's can become more central voices [62] to the curriculum with experience. The consideration of context and theory helped me understand how LAs can be leveraged as pedagogic consultants in courses where a community of practice may be present.

The precedent of listening to students in qualitative physics education research helps me show that meaningful ideas for curricular improvements can come from students. The experience of using SaP and CoP in Chapters 4 and 5 helps me understand the importance of providing theoretical structure and attending to context when consulting students about their experiences. Next, I describe a type of curriculum that is newly developing and widely spreading [39, 33, 64, 65, 66, 67, 68, 69, 44], indicating a significant opportunity to learn from student perspectives at the nascent stages of this curriculum's development .

2.2 A context where students' perspectives are needed: computation-integrated physics

Curricula in physics classrooms across the United States have been changing over the last fifteen to twenty years to include the integration of computational modeling into curricula as a tool to learn physics [41, 42, 43]. The goal of this integration is for "students [to] use computing as naturally as they [now] use traditional mathematics" [39]. Just as mathematics is taken for granted as an essential tool for learning physics, the hope is for computation to be integrated into physics curricula just as deeply. Because computational modeling is becoming a critical part of STEM careers [70, 71], it is also becoming increasingly important in curriculum development [33, 64, 65, 66, 67, 68, 69, 44] and in national learning standards [24, 25, 26, 27]. Because of the broad scope of this goal and widespread integration, there are many different types of computational integration [33, 64, 65, 66, 67, 68, 69, 44]. The variance among implementations means there are many different opportunities to incorporate student perspectives into the new and changing curricula.

This variance is motivated by and reflected in the wide-ranging, often ambiguous national calls and standards that give structure to the integration of computation into school STEM [24, 25, 26, 27]. They describe broad learning goals, like using "computational tools...to analyze, represent, and model data" [24], or "choose among computational algorithms and computational tools to produce a solution" [27]. There is not much specificity provided about how to achieve these learning outcomes, so the implementations have varied greatly, even in the last few years [33, 64, 65, 66, 67, 68, 69, 44]. A recent call has emphasized the lack of direction in HOW to integrate computation into STEM courses and provided some guidelines for integration and recommendations for research that can strengthen and deepen the research-based support for computational integration [33]. One of the major recommendations from the call was to "examine the development of students' identity, agency, positioning and motivation in relation to their engagement in computational tasks" [33]. This need for understanding how students relate to computation on an affective level is a gap that I intend to address with this dissertation.

Some research has attempted to coordinate the perspectives of faculty and professionals into computation-integrated physics curricula or learning goals related to it [72, 71, 70, 73], but none have consulted students themselves about their experiences or for direct input into what matters when learning computation-integrated physics. Pawlak et al [74] produced a research study adjacent to this endeavor by seeking to understand computation-integrated physics learning from the perspectives of LAs. In the context of physics without computation, student perspectives have been consulted for rethinking curriculum [29, 75], but this type of work is still needed in computation-integrated physics. One way to address this need is by observing students working on computational activities in their physics class, and cataloging learning goals based on their experiences as done by Weller et al [76]. However, this method still requires researchers to interpret students' experiences rather than hearing students' interpretations for themselves. A more direct, affect-based approach would be to focus on interviews as a data source, where students can say directly what they struggle with and how they feel about it. This is the study presented in Chapter 6.

Outside of computation or computation-integrated contexts, researchers have used student perspectives and affect-based studies to better understand STEM courses and to motivate change in STEM pedagogy [77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 14, 88, 89, 90, 91, 92, 93, 94, 95]. For some examples, Hannula [80] demonstrated connections between affect and success in a middle school math context, suggesting that teaching and learning can be improved by attending to student affect in pedagogy. Galloway et al [84] asked students in an undergraduate chemistry lab course about their experiences, finding that students had complex, multifaceted affective responses. This led the authors to develop pedagogical suggestions for cultivating positive affect and making lab-based chemistry more meaningful for students. Alsop and Watts [87] examined how students felt about and perceived radiation and radioactivity in their physics class, finding that it was possible to keep students engaged but not off track by striking a balance between staying informed and following passions and interests. These examples align Section 2.1, where I showed that student perspectives can enrich curriculum when their input is incorporated in structured ways. This further emphasizes the importance of addressing the need to research student perspectives in computation-integrated physics.

While Chapters 4 and 5 focused on the LAs in an introductory-level university physics class, Chapter 6 specifically emphasizes the student perspective. In Chapters 4 and 5, the LAs operated in an environment that had been around for a few years [63], and physics LAs have precedent for participating in physics education research [96, 97, 98, 99, 34, 100, 101, 102, 103], meaning our studies were built on a longstanding foundation of listening to LA perspectives. In contrast, there is a lack of foundation for research on student perspectives in computation-integrated physics. Though faculty perspectives have been consulted in computation-integrated physics education research and student perspectives have been consulted in other disciplines, as I described above, we need to fill the specific gap of students' perspectives in the context of computation-integrated physics. Due to computation-based integration being a novel research area, the research design in Chapter 6 is more exploratory than the previous chapters. Since so little is known about computation-integrated environments, the intention of Chapter 6 is to build a foundation upon which more focused research can be built. This exploratory research will facilitate future steps towards the act of incorporating student perspectives into curriculum. For Chapter 6, I primarily used students' interview comments and the context of the classroom to explore the landscape and meaning of students' experiences. To build a structure, so to speak, I sought to understand how affect-based theories interacted in the context, which I detail in the next section of the literature review and in Chapter 6.

2.3 Laying the foundation for incorporating students' perspectives in computation-integrated physics

This section is about providing a background for designing research that listens to students in a computation-integrated physics environment. Chapter 6 uses a broad study design, and the breadth of the array of student experiences led to a decision to catalog their perspectives using context to gain insight into what the students meant. The focus was mainly on how computation brought about new experiences for the students. However, once I analyzed the students' perspectives, it became clear that some of them related to established theoretical constructs from parallel, student-centered studies that used those theories [104, 105, 92, 93, 94, 95, 106, 107, 108, 109, 110, 111, 14]. I plan to briefly review the relevant theories below to provide context for Chapter 6. To instigate significant change, I would need to focus more deeply on applying a theoretical framework to the students' perspectives and processing their experiences through a lens that can help understand what these perspectives mean for potential curricular change (like in Chapter 7). I address that line of reasoning in the next section, but here I review the theories that featured in Chapter 6, which have been used to explore computation-integrated STEM contexts, albeit minimally.

The first theoretical lens is self-efficacy. As defined by Bandura, self-efficacy is "concerned with judgments of how well one can execute courses of action required to deal with prospective situations" [112]. In relation to students' motivation and confidence for a given academic subject, he said, "the higher the students' beliefs in their efficacy to regulate their motivation and learning activities, the more assured they are in their efficacy to master academic subjects" [113]. This construct has been used widely in studies focused on understanding how students' affect relates to their view of their own abilities [104, 105, 92, 93, 94, 95]. While not quite the same as our context of computation-integrated physics, self-efficacy has been used in technology-based interventions aimed at improving self-efficacy for physics [114, 115], physics-based interventions aimed at improving computational thinking [116], and one experimental study aimed at characterizing and supporting teachers' self-efficacies for teaching computation-integrated engineering [117]. These studies took a focus towards the outcomes of their interventions, and their contexts were physics or computation but not both. The perspectives gathered in Chapter 6 included students discussing their abilities in relation to specific computational or physics activities, so it was necessary to provide a preamble describing previous applications of self-efficacy in computation and physics to ground our findings in previous research.

The second theoretical lens is self-concept. Marsh and Craven [118] provided a definition for self-concept, based on the work of Shavelson et al [119], as "one's self-perceptions that are formed through experience with and interpretations of one's environment. They are influenced especially by evaluations of significant others, reinforcement, and attributions for one's own behavior." A person has a different self-concept depending on the context (e.g., physics class) and focus (e.g., computational activities) [119]. This construct has been used widely in studies focused on understanding students' affect as related to how they view themselves in an academic setting [109, 110, 120, 111, 14]. Despite the wide use and focus of self-concept on students' perceptions, I could not find any application of self-concept at all in published research on computation-integrated physics. The closest approximation is research on self-concept related to students' perceptions of relevance in their physics curricula [14]. The perspectives I gathered in carrying out the research of Chapter 6 were relatable to self-concept, which provided an opportunity to explore the data's relationship to theory given the lack of studies on self-concept in physics or computation, let alone computation-integrated physics.

The third theoretical lens is mindset. Originally theorized by Dweck [2], it can be thought of in terms of how "students may hold different theories about the nature of intelligence" [4]. In this sense, mindset is a "continuum," where on the one end students believe their intelligence is “an unchangeable, fixed entity,” and on the other end it is “a malleable quality that can be developed” [4], but in reality students may hold views anywhere between these points. Mindset has also been shown to change over time and vary depending on context [106, 121]. As a framework, mindset has been used in education research to show how students’ mindsets relate to how they respond to their experiences in educational settings [106, 107, 108, 121, 122]. In computation-integrated STEM, mindset has been used in limited ways so far. It was used once in a two-week intervention where physics students did a computational project and experienced no significant changes in their mindsets [123]. It was also used by Little et al [122], who applied mindset to develop a mindset-based coding scheme and describe students’ interview comments about the challenges that they faced in class. While three of the 21 interviews that compiled Little et al’s [122] coding scheme were from courses that had computational projects integrated into them, the majority of interviews were from contexts outside of computation-integrated courses. The potential presence of mindset in students’ perspectives in Chapter 6 and with the lack of mindset-based studies in primarily computation-integrated physics contexts provide an opportunity to address mindset in my data.

Based on the literature outlined above, it makes sense that some of the students’ perspectives around computation ended up relating to the theories of self-efficacy, self-concept, and mindset. In truth, it is not surprising that these theories emerged from students talking about their experiences with physics and computation, but I did not intend to investigate any particular theory at the outset of the research. I instead aimed to build a broad understanding of the challenges students experienced from their points of view. As the area of integrated computation is relatively unexplored, providing a broad perspective makes sense as the first step towards deeper investigations into how these theories manifest individually and relate to each other in a computation-integrated learning environment. I provide a base of literature here on the landscape of research in computation and physics relating to these theories to scaffold a discussion in Chapter 6 about how these theories could be related to each other in our context. From there, further research can build on more specific constructs with a stronger theoretical base, like the use of mindset in Chapter 7, which I discuss in the next section.

2.4 Building on my previous work to highlight and address a curricular need in computation-integrated physics

In Chapter 6, I found that students' statements were related to the constructs of mindset, efficacy, and self-concept. This study highlighted the need for more detailed investigations in the future to understand how they impact students in the computation-integrated environment. In Chapter 7, I addressed one aspect of this need by designing a study that listens to student perspectives with both theory and context in mind. This study carries implications that are based on student perspectives and that have the potential to improve student affect and learning in computation-integrated physics.

I chose to focus Chapter 7 in part on the theoretical lens of mindset (one of the theories I applied in Chapter 6) for two reasons. First, mindset is connected closely with improving students' outcomes, specifically through interventions [124, 125, 126, 127, 128]. The aims and outcomes of interventions range among improved mental health [125], increased motivation [124, 127], and boosted academic performance [126, 128]. Using the connection between mindset and the benefits to students provides a motivation for understanding students' perspectives with a mindset lens with the hope to ultimately use those findings to potentially infuse mindset-fostering practices into a computation-integrated physics curriculum.

The second reason I focus on mindset is that it is connected to the theoretical Computational Thinking (CT) Dispositions Framework [1]. CT itself is a widely sought learning goal for instructors in STEM contexts [129, 130, 131, 132]. Historically CT has had a variety of definitions, but one widely supported operational definition of CT [132] splits CT into a framework with two connected categories: practices included in CT (such as using algorithmic thinking to automate a solution or representing data with a model) and dispositions that support and enhance the practices (such as persistence through challenges). There is a wide array of research focused on CT practices [40, 133, 66, 134, 76], but very little focused on CT dispositions [1]. Pérez designed the CT Dispositions Framework, using aspects of mindset and mindset-based research, to address this need. He named three dispositions as central to the framework: having a tolerance for ambiguity, persisting on difficult problems, and being willing to collaborate with others [1]. For each disposition, Pérez argued that there are three aspects of the disposition that interact with one another: inclinations are tendencies for a person to think or act in particular way, sensitivities are a person's awareness of opportunities to engage an inclination, and abilities are how effectively a person can act on those opportunities [1]. By dividing each disposition into its corresponding inclinations, sensitivities, and abilities and describing each aspect in detail, Pérez produced the CT Dispositions Framework [1]. However, Pérez's framework to this point is a theoretical construct developed in a math context. There is a need to explore the aspects of CT that Pérez pointed out in his CT Dispositions Framework and how they apply to different contexts. This is especially true because CT is highly desired as a learning goal and dispositions are understudied in comparison.

Because of this need and CT dispositions' connection to mindset, Chapter 7 examines how students in a computation-integrated physics classroom express CT dispositions and how those expressions relate to mindset as well. By connecting the newly developed CT Dispositions Framework [1] with the well-established theory of mindset [2] and by building on a foundation (Chapter 6) of exploring how mindset shows up in computation-integrated physics, I intend to show the applicability of the CT dispositions framework in a computation-integrate physics context and how it may be used to meaningfully and productively impact computation-integrated physics curricula. The opportunity to do this rides on the history of listening to and incorporating students' perspectives into curriculum in research-based ways, the need for such work in computation-integrated physics, and a context-heavy, student-centered foundation (Chapter 6) for the more theory-driven approach of this particular opportunity (Chapter 6).

2.5 Summary of literature review

In summary, there is a precedent for incorporating students' perspectives into curriculum design. Either using students' perspectives to build theory or using theoretical frameworks to process students' perspectives. It is clear that keeping contextual factors in view when attempting to interpret and use student perspectives are crucial to make meaningful, productive changes to curriculum that benefit students. The qualitative research on this topic provides some footing for my own research, which aims to provide in-depth understanding of what students can tell us about their experiences with computation-integrated physics. Computation-integrated physics is a widely spreading context for which student perspectives have not yet been used in curriculum design. My research in this area is situated by calls to investigate students' experiences and perspectives. I orient my research as developing a foundation from which students' perspectives can be further explored in the context of computation-integrated STEM courses. CT dispositions and mindset provide an opportunity to build on this work by gathering students' perspectives on computational integration and translating their perspectives into implications for future curricular change and new implementations of computation-integration physics.

CHAPTER 3

METHODOLOGY

In this dissertation, my focus is on how the perspectives of students can lead to improving curriculum and pedagogy. Much of the work I do is to elicit, observe, and report on their feelings about computational modelling (in the case of a computation-integrated physics class) or physics pedagogy (in the case of learning assistants). The research itself is qualitative and detailed because the goal is not to generalize across contexts (using induction) but to build understanding of behavior in particular situations (abduction) [135]. I cannot distill the experiences of these students into parameters through which results can be interpreted and generalizations can be induced, but I *can* gain an in-depth understanding of a small group of students, which can then be used to make connections and gain insights to other narratives about computational modeling in high school physics or physics pedagogy at the introductory university level. Everyday experiences that persist longitudinally—such as being a high school science student or an undergraduate learning assistant—cannot just be factored into components and reapplied elsewhere. This has driven my choice of a qualitative methodology. With this dissertation, I aim to offer a deep understanding of one context that others may use to make sense of their own.

The methodology I use in the following chapters is qualitative case study [46, 47, 48, 49, 7, 50, 51, 52, 53, 54, 55, 56]. This is a way of constructing truth from the perspectives of participants and from the artifacts they produce. With case study, one can test out ideas about how things work to see what is really going on in the lives and everyday settings of the student participants. This is similar to how Stake [46] describes case study's main functions: (1) creating explicit formal knowledge about the phenomenon and (2) creating a vicarious experience for the reader. Below I define case study and flesh out the purposes that it can serve.

3.0.1 Definition and purposes of case study

Case study is defined by the natural setting of the research context and multiple data sources [46, 48, 50, 51, 54]. The natural setting ensures that the phenomenon of interest plays out authentically, and the multiple data sources ensure that evidence can be triangulated together for strong claims when carrying out analysis on the data [7, 48, 47]. A case study is characterized by the case and the phenomenon. The case is the site of the research, sometimes a specific place, individual, or organization/institution [46, 47, 48, 49, 50, 51, 52, 54]. This can align with the context but does not have to (e.g., if the case were an individual person). The phenomenon is an aspect of the case that the researcher focuses on, like an action/practice, event, individual, or idea [46, 47, 50, 51, 52, 54]. Sometimes, the case is just an instance of the more general phenomenon. Together, the case and the phenomenon form the research question in a case study [46, 50, 51, 54]. As an example, Ozen [17] studied a physics classroom in which the teaching primarily took place online. The case was the online class, the phenomenon was how students perceived their experiences in the online class, and the research question was, "What are the students' perceptions of an online College Physics course as taught through the Internet?" [17].

A feature of the case studies in this dissertation is that their data sets are bounded [47, 48, 46, 49]. It is important when designing a case study to specify what belongs in the set of studiable data because the context can have drastic impacts on what and how data are generated. Since the context ties the case to the phenomenon, and this context can include both time AND space, the context plays an important role in the planning stage of a case study. When deciding how to generate data, an important question is, what in this context is relevant to the case? In designing for data generation, it can help to understand how data comes together and how different types of data can strengthen the validity of a case study. Understanding what data is used for in a case study is crucial for designing where and how to generate data. In Figure 3.1, I provide a photocopied figure from Erickson [7] that shows how multiple sources of data and evidence (e.g. field notes, interview comments, and site documents) can be organized in a case study, specifically noting how multiple sources of data are used together to create subassertions (or claims) and ultimately construct the

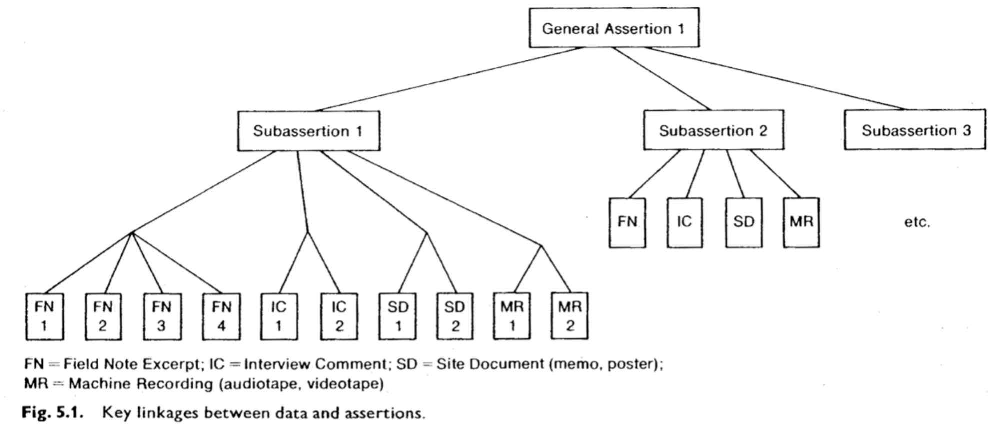

Figure 3.1: Diagram from Erickson [7] about the organization of the links between data and assertions in a qualitative case study.

general assertions in the study.

While all case studies fall under the umbrella of gaining an in-depth understanding of a phenomenon in a particular setting, they can serve a variety of purposes in research. Sometimes, a case study is an existence proof [47]. An existence proof documents a phenomenon to show that it can be done, and wherever it's not done it is because of choices, not because it is impossible. Chapter 5 is in part an existence proof of LAs participating in a student partnership on the development of curriculum and pedagogy. On the other hand, a case study that serves as a falsification shows that some general idea is not always true (e.g., all cultures develop arithmetic) [55]. Case studies can also provide counter-narratives [48, 136, 137], much like falsification, but specifically showing that the dominant idea does not necessarily describe the phenomenon accurately (e.g., a study countering the narrative that Danish Muslim girls often do not play sports because of their religion [138]). The difference between these two functions is subtle: falsification proves an idea wrong that was generally thought to be true, whereas a counter-narrative provides nuance to an idea that was thought to be more straightforward.

Case studies can also generate theory about how a phenomenon works [46, 47, 49, 56]. This is often groundbreaking and provides a new way of understanding a particular phenomenon. Building on that, case studies can also substantiate or test the generated theory in other contexts to see how the theory extends to other situations [55, 139]. This parallels the theory-generating work of Pérez [1] on CT dispositions and my extension of his theory into the context of computation-integrated high school physics in Chapter 7. At other times, case studies can generate hypotheses [47, 56], which in turn could motivate quantitative work. Designing a quantitative study beforehand often misses data collection on the important factors that case studies could reveal.

All case studies contribute to a repertoire of stories [140, 136]. This means that for a given phenomenon, there are many case studies of that phenomenon in a variety of contexts. The cases one can access via the repertoire of stories can help provide insight to the phenomenon at large or to deal with unexpected issues related to the cases. The next four chapters all serve this purpose along with their other aims.

3.1 Traditions of case study

Case study can be categorized more formally than by its purpose. Over the history of case study's use, different traditions have emerged that align and differ in how the research is designed and how claims are constructed from evidence. Contemporary use of qualitative case study can generally be described with three categories: interpretivist, realist, and comparative. Below, I describe what each tradition offers, how they differ and align with one another, and how I used them in this dissertation.

3.1.1 Interpretivist Case Study

The hallmark of interpretivist case study [46, 50, 51] is the importance of language in framing the case. Language is what constructs the case itself and gives insight into how the case is being interpreted by the relevant characters. For example, what makes a place function as a classroom is how people interact in that place and what they say. There are artifacts that reify and facilitate the interactions, such as whiteboards and desks and lab equipment, but what matters most is how the teacher and students come together and perform the ritual of school-based learning. Interpretivist case study believes in studying what participants say and do, focusing on how they interpret the phenomena that play out in their setting.

Interpretive case studies investigate how a phenomenon is socially constructed and what it means to its participants, hence the focus on interpretations. Phenomena of interest in interpretivist case studies are often commonplace ideas that do not have fixed meanings, instead they mean different things to different people. Researchers aim to unpack how others interpret that *thing*. We seek to enter the participants' "imagined world" [50] and understand the phenomenon from their point of view.

The mechanism used in interpretivist case study to connect data to claims is called "anchor points" [50]. These are the perspectives of the participants that emerge from data generation. Each perspective serves as an anchor to the phenomenon, which is understood by generating multiple anchor points and making inferences based on how participants interpret it. After all, the interpretations of participants socially construct the phenomenon in the first place, so in the frame of interpretivist case study, the closest data sources to the phenomenon itself are the perspectives of those who participate in it.

Interpretivist case study emphasizes the social construction of the phenomenon. Within a single context or activity, the participants may be focused on several different aspects of the activity, and they may interact in several different ways in pursuit of several different goals. Even within a single context or activity, many cases or phenomena could be constructed, because according to the interpretivist stance, everything that the participants view as meaningful *is* meaningful [50]. This orientation towards participants' perspectives is what led me to use interpretivist case study as much as possible in my work.

The way I incorporated interpretivist case study into my research designs was to formulate research questions, data generation methods, analytic methods, and assertions with the perspectives of my participants at the center. For example, Chapter 5 [31] was designed with interpretivist case study. The research questions were aimed to explore how LAs interacted with one another and with aspects of the course (e.g., "how has the practice of feedback been shaped by the LAs?"). The questions in the interview protocol were designed to be more open-ended [45] so as to allow LAs to tell me what *they* thought was important (e.g., "How do you know if a student is struggling?"). The data generation methods were to allow LAs to provide their perspectives through a variety of means (e.g., interviews, feedback excerpts, email correspondences). The analysis and findings were also shaped around what LAs said and did in the data—I treated each LA-centered data source as an "anchor point" [50] through which to construct an understanding of the meaning that LAs assigned to the phenomenon. Due to my focus on students' perspective throughout the dissertation, not just in Chapter 5, all four of the following chapters take up this interpretivist stance to some degree.

3.1.2 Realist Case Study

In contrast to the interpretivist approach, a realist case study takes more of an inductive approach to case study research. Yin [47] provides a realist point of view on case study, arguing that the difficulty of case study research lies in there being many more variables of interest than data points. Rather than focusing on the interpretation and experience of the phenomenon through the participants, realist case studies focus on distilling the holistic and meaningful features of the phenomenon itself. While subtle, there is a distinct difference in the goals of these methods. Interpretivist case study focuses on the participants' interpretations of the phenomenon, whereas realist case study focuses on the phenomenon, using participants' interpretations (among other data) to describe it. In a realist case study research design, there are five components [47] that shape the study: research questions, propositions, units of analysis, logic models, and rival explanations.

First, research questions are targeted by using the literature to narrow the topic of interest, identifying interesting questions stemming from that literature, articulating some potential questions of one's own, and sharpening and supporting those questions with more literature on the same or similar topics. Second, propositions are ideas for how the relationships of interest within the research question come about [47, 49]. Propositions help create ideas for where to generate data, and what components of the case are most interesting for research.

Third, units of analysis compose the case [47]. Units of analysis refer to the data sources as characterized by how they are grouped in the research design. For example, in an interview study, one could frame each conversational turn as holding valuable information, whereas someone else may argue that it would be more valuable to analyze the interview in larger chunks based on the interview questions. Both approaches may hold merit in different ways, but in one case the unit of analysis is a conversational turn, whereas in the other case the unit of analysis is a larger episodic chunk. The research questions and propositions help with deciding how to generate data from the unit of analysis. Realist case study delineates between different structures for the unit of analysis.

Fourth, logic models [47] are what link the data to the propositions. They are a series of logical steps that map analytic techniques onto the generated data. The logic model, which describes how evidence will be constructed into claims, has a clear function during data analysis, but it can also help when deciding how to generate and represent data in the first place. Hollweck [141] provides a helpful interpretation of Yin's [47] definition: "logic models...can help explain the ultimate outcomes because the analysis technique consists of matching empirically observed events to theoretically predicted events" [141]. Fifth and last, rival explanations are also important to realist case study because they represent how others may conceive of the phenomenon of interest. When building claims in a realist case study, one is often compiling a set of the most important variables into an explanation of the phenomenon. By anticipating and addressing alternative groupings of variables or alternative explanations, one can strengthen the findings of a realist case study.

Due to its focus on identifying relevant variables, realist case study can often employ techniques like experimentation, correlation, statistical analysis, and quantitative and/or mixed methodology. This is popular in science and sociology [47, 56, 139]. For my dissertation, which comprises completely qualitative case studies, a realist stance does not make total sense, but I do use components of realist case study in Chapter 7, taking precedent from prior combinations of interpretivist and realist case study [142, 143, 144]. This combination is described further in Chapter 7, but in short, the advantage of this approach is that I can retain a focus on students' perspectives (interpretivist) while applying structural features of a realist case study (e.g., propositions) that help organize assertions around a theoretical framework.

3.1.3 Comparative Case Study

Comparative case study focuses on the people, situations, and events that comprise a context and on processes by which those objects interact [53, 54]. Though I did not use comparative case study in any of the chapters of this dissertation, it is worth reviewing to compare it to interpretivist and realist traditions and to give further context for what research design choices one makes when choosing to employ a case study methodology. Comparative case study is a relatively recent development (last ten years [53, 54]) in case study methodologies, and it provides some attention to aspects of a case that interpretivist and realist case study do not attend to [53]. In this section on comparative case study, we focus on the features of this methodology that contrast with interpretivist and realist.

One idea unique to comparative case study is that the research design is constructed along three axes across which the context spans: horizontal (meaning across similar cases), vertical (meaning at varying scales), and transversal (meaning back through history) [53]. By looking across these axes, the researcher can gain insight from comparing across cases (e.g., two different schools), strengthen findings by tracing them across different scales (e.g., classroom, institution, national curriculum standards), and situate the work in the context's history (e.g., school's history). By expanding the scope of research like this, comparative case study is resistant to bounding the sources from which data will be generated [53]. This perspective on boundedness helps me point out that my case studies, which draw more from primarily interpretivist traditions, are bounded in the sense that they draw from a limited pool of data sources by design. Each approach has its merits: unbounded research allows the researcher to examine everything that could be important for explaining the phenomenon, whereas in bounded research, the researcher examines fewer data sources and so can perform a more in-depth analysis of the phenomenon.

Given the name, comparison is the defining feature of comparative case study [53]. Comparison is what brings significance to the research by addressing how insights drawn from different cases are related. This relationship is what is most strongly applicable to other, unstudied cases. In the context of case study, comparison can mean one of two different processes. Homologous comparison is across similar (grain-size) sites [53]. Heterologous comparison looks at similar phenomena or policies across different kinds of entities in terms of scope (e.g., looking at how bankruptcy affects a small business versus a family) [53]. The focus on comparison contrasts with my non-comparative use of interpretivist and realist case study. Comparative case study argues that insights mainly come from comparing across cases and working outward to new data sources. I instead chose to investigate with a focus on producing an in-depth look at the local, observable interactions that occurred within each of my cases.

To be clear, my prioritization of depth did not prevent me from examining contextual factors or new data sources. An alternative framing for this dissertation could be that Chapter 5 represents an unbounding and re-exploration of Chapter 4, and Chapter 7 represents somewhat of a heterologous comparison looking at how the CT dispositions framework operates when applied to a context different from the one in which it was developed. The reality of my research designs was that I was interested primarily in using students' perspectives, and interpretivist case study made the most sense for addressing that priority. Incidentally, realist case study made some sense for parts of the design of Chapter 7, as described in Section 3.1.2.

3.2 Use of case study

Case study can be used for a variety of purposes and via different traditions as described above. The chapters of this dissertation also use some of those purposes and traditions. It remains to characterize the process of carrying out a case study. A key feature in carrying out a case study is using the context and the research questions as a flexible guide rather than "an ideological commitment to be followed whatever the circumstances" [47]. You spend a lot of time with the generated data, writing narratives about it, attempting to explain what you are seeing, and getting to the point where you know the data intimately. Often after researching a specific phenomenon and playing around with the data, it can become clear that the research question could be better explored by widening the angle of the research (see for examples, Chapters 5 and 6). This can turn a straightforward research question into something new and interesting by exploring the phenomenon from a new angle. This change in angle comes about from greater knowledge about a context, and as a response, an informed shift in the approach. This shift in approach is a hallmark of case study research which is also part of what makes it so powerful [50, 51, 53]. By allowing for flexibility in research design—for example, by generating new data or applying theories to data iteratively—one produces research that is especially well tailored to the phenomenon of interest. Adding this strength to the *depth* that case studies provide makes qualitative case study an ideal tool for researching misunderstood or under-understood phenomena.

Another language-based feature of the following chapters is that I use the term "data generation" rather than data collection [48, 145] (e.g, Prasad [146], Bannerman [147]). This is a choice to acknowledge the role of the researcher. I designed the studies, chose where to place the cameras and microphones, chose which students to interview based on field notes that I took, created questions for interview protocols, carried out the interviews, and created and/or edited the transcripts. The idea of generating data implies someone is creating it, which is largely true—when I analyze data, it is data that I played a role in creating. Without my intervention, much of the data (e.g., interviews, field notes) would not have existed. It would not be totally accurate to call this process "data collection," as if the data were already there and I simply swooped in to extract it, as if the perspectives of human participants could be essentialized like that. Doing so would claim an objectivity in this research that simply is not there [46, 50, 51, 53, 54].

There are also limitations of case studies. As Yin puts it, case studies do not unearth causality, but they are still useful in explaining how and why a relationship exists [47]. They do *not* provide causal or correlative results, nor can be generalized to a broad audience. That is what quantitative studies are for. Case studies are for studying interactions that exist within a phenomenon in which humans participate. It is towards these interactions and participants that I attempt to orient the following chapters.

CHAPTER 4

LEARNING ASSISTANTS AS CONSTRUCTORS OF FEEDBACK: HOW ARE THEY IMPACTED?

This chapter represents my first exploration of students' perspectives in a research context, which was a flipped, introductory physics course at Michigan State University. Though the course had computational activities integrated into it, this was not the focus of my research at time. Instead, this was an initial exposure to a model of listening to students to gain insight into how a course impacts its participants. This study was geared more towards the impact on a single undergraduate learning assistant rather than a group of students, but it fostered in me an interest in qualitative case study and students' perspectives, which I pursued with a more in-depth study in Chapter 5. This chapter was published in the proceedings of the 2018 Physics Education Research Conference [60].

4.1 Abstract

Project and Practices in Physics (P-Cubed) is a flipped section of introductory, calculus-based physics, which is designed with a problem-based learning approach where students work in groups on complex physics problems. Learning Assistants (LAs) are critical to the course, where they each function as a primary instructor for four to eight students by asking questions and prompting discussion during class. LAs in P-Cubed also write individualized weekly feedback to each of their students, which is meant to offer suggestions to the student for how to improve their work in class and provide the student with a justification for their in-class grade. We conducted semi-structured interviews with LAs to examine the ways that they construct feedback and how this impacts their own experiences as students taking classes. In this paper, we examine and discuss the reflections of one such LA as a case study for the impact feedback can have.

4.2 Introduction

It is not a new idea that physics Learning Assistants (LAs) are impacted significantly by their experience in the LA Program. The experience can be transformative with respect to their identities as physicists [99], how they teach physics [148], and even their metacognitive development [149].

At Michigan State University, LAs are employed to work in the environment of Projects and Practices in Physics (P-Cubed), a flipped section of introductory, calculus-based physics, which is designed with a problem-based learning approach where students work in groups on complex physics problems [63]. The LAs work ten hours per week and fulfill three duties: (1) Each LA functions as a primary instructor for four to eight students by asking questions and prompting discussion during class. (2) LAs meet twice weekly to prepare for teaching and once weekly to debrief and reflect on how the week went. (3) LAs write personalized feedback for each of their students on a weekly basis. This last expectation for LAs is uncommon at other universities, for we could not find any published research mentioning such a requirement for LAs. The feedback LAs provide is intended to be formative by giving students guidance for improving their scientific practices within their in-class group work [150].

The intention behind individualized weekly feedback is to offer suggestions to the student for how to improve their practices and provide the student with a justification for their in-class grade, which comprises 20 percent of the total grade for the course. To this end, feedback is split up in two parts to address both how the group performed and how the student performed within the group. In each part, the LAs are to include something the student or group did well, something to work on for next week, and a strategy for how to work on it.

There is precedent from existing research [99, 148, 149] to look at how the LA experience as a whole impacts LAs, but reducing the grainsize to look at specific aspects of the LA experience is much more rare. This presents us with an opportunity to look at the LA experience and report out on it in a new way. This is especially interesting since the piece of the experience at which we are looking—feedback construction—is distinctly a part of being an LA in P-Cubed.

As mentioned earlier, the feedback in P-Cubed exists to help the students improve their scientific practices, and we postulate this impact extends in some way to the LAs who practice constructing the feedback. The undergraduate LAs hired for P-Cubed were all once students in the class, so we also intend to piece apart how *receiving* feedback plays into the impact of constructing it. With this mind, we pose three research questions: (1) How does constructing feedback affect decisions LAs make outside of P-Cubed? (2) How does receiving feedback as students affect LAs's approaches to constructing it? (3) How are the impacts of constructing and receiving feedback connected for LAs?

4.3 Methods

We selected three LAs to each participate in a recorded, semi-structured interview, which was intended to probe at how the LA approaches feedback construction and how their experience as an LA and as a student in P-Cubed might have impacted other areas of their lives (e.g., study habits, working in groups in the workforce). We selected LAs to portray a broad range of approaches to feedback. Alvin is in his second semester of being an LA. He is a sophomore physics major. Bella is recent graduate who has been in the workforce for a couple months. She was an LA for three semesters, and she studied biochemistry. Carly is in her fourth semester of being a P-Cubed LA, and she is a junior majoring in biosystems engineering. All the LAs we interviewed are white.

We constructed [48] a pilot interview protocol meant to dig into three things: (1) We wanted to learn about each LA as a student in other classes, so that they could reflect on experiences they have had in contexts outside of P-Cubed—contexts in which feedback construction may have made an impact. (2) We wanted to learn about how each LA interacted with the feedback when they were a student in P-Cubed, because we thought that experience would play a big role in how the LA interacts with feedback construction. (3) We wanted to find out how each LA approaches feedback construction itself, because that experience is central to the impact feedback construction has.

The first two interviews were with Alvin and Bella. The protocols used were very similar, the only difference being some questions were rephrased to give Bella the opportunity to speak about her experience in the workforce. The protocol was modified significantly for Carly's interview, with potential follow-up questions listed and pauses built in based on preliminary analysis and reflections on the first two interviews. The goal of the modifications was to develop a more comprehensive view of Carly's experience with feedback construction than we were able to develop for Alvin or Bella. These interviews are the first three among a larger ongoing investigation, for we intend to interview additional LAs in the future to broaden the insight we make from our interviews with Alvin, Bella, and Carly.

In our analysis, we focus heavily on Carly's interview. The reason for this is hers has the richest data. This reality is owed partially to her willingness to reflect deeply on her multi-year LA experience, but also to the iterative development of the interview protocol, as described above. Carly, as the third participant, was given the best opportunity to express how the feedback impacted her, and more importantly she was prompted explicitly to think about and discuss ideas related to this impact—Alvin and Bella were not asked to discuss their experiences in the same way. However, Alvin and Bella did reveal enough to make us believe that there exist themes traceable between LAs, and perhaps the feedback has impacted Alvin and Bella in personally meaningful and lasting ways, even though they do not articulate the impact in the same way that Carly does.

We decide to align our research here as an explanatory case study [151], due to the limited theoretical background on the impact of individualized written feedback on its writer, and because the boundaries between the feedback's impact and the impact of the rest of Carly's LA experience are not always clearly evident. Carly was chosen as a critical case in investigating what effects giving feedback would have on an LA and how those effects occur. We specifically use logic models [151] to construct a theory of how Carly's experiences with feedback interact with one another.

4.4 Results and Discussion

Alvin clarifies the feedback's impact on his own life when he is asked to reflect on what feedback construction means to him:

> "Me thoroughly contemplating what advice to give somebody, is also me...really thinking about good things to do...when I am in a group in the future and I have a similar situation... So if I tell a student of mine that this is a good way to improve when you have this sort of situation in your group, then, me having thought about that, and how to write feedback, will help me in the future when I am in a similar situation in a different group" – Alvin

Alvin's quote demonstrates a theme that showed in Carly's interview, too, which is that feedback construction helps LAs think about their own group work outside of P-Cubed and respond in thoughtful ways when difficulties arise. We explore this phenomenon in more detail in the following case study of Carly. Her perspective on feedback is built out of a multitude of experiences, and she is able to articulate this perspective clearly. As we will demonstrate, her own experience mirrors Alvin's reflection in the quote above, which suggests that the impact the feedback has had on Carly is not anomalous.

4.4.1 How constructing feedback affects decisions Carly makes in other contexts

Carly's take on how feedback construction plays into other areas of her life echoes Alvin's:

> "Writing feedback, it's easy to look at a group of people working together and be very objective about how everyone is behaving within that group. But then when you're in a group—to then be able to step back and reflect on your own group and how you're acting in that group—I think that's what...I've taken away...If I'm in a group and I'm getting frustrated, then it's like, 'Okay, what would I tell someone to be doing in this situation?"' – Carly

She highlights a strategy of relating her difficulties with group work to the same sorts of issues that might come up for a group in P-Cubed. She also makes an important point that writing feedback is not an isolated exercise—it involves observing behavior in class as it plays out. To understand how Carly enacts this strategy in real life, we asked her to give an example, and we believe the recollection she produced speaks richly to what the feedback's impact can look like for an LA. As part of a group, she came across a dilemma (which we will refer to as The Dilemma), and she believes her reaction derives from her experience constructing feedback. We retell how The Dilemma played out and use evidence from what Carly says to show that the feedback impacted her response in the ways that she claims. First, it is helpful to know how Carly sets it up:

> "I'm in a design group right now. Three of us get along really well. One guy is very inconsistent as to when he's there, but he puts a lot of work in, but it makes it challenging because we'll have done something and he will have missed all of it for no apparent reason... He'll come to the next meeting and be like, 'Oh, look at everything that I've done'. And we're like, 'Well we calculated that already, and we assumed these numbers, and you assumed these [other] numbers...so this is what we're gonna go with.' But, you have to be very tactful in how you say that." – Carly

Carly's dilemma is that one member of her group went off and did a lot of unnecessary work, and now the group needs to figure out a way to tactfully bring him back into the fold. Carly admits, *"I tend to...kind of be the leader of the group"*, and the decision is hers to make. Carly ended up making the decision for the group to sit down for a couple hours, step through the calculations everyone had done, and come to a consensus together about what approach the group should use moving forward. The result was beneficial to the group—the group adopted some ideas that the fourth group member had found while doing his own calculations, and maybe more importantly, he was brought back into the group without feeling devalued.

Next, we intend to unpack the forces that played into Carly's thought process in the way she described it. The way she outlines her ability to *"step back and reflect"* when speaking generally about The Dilemma in her first quote shows that she traces her tactful response to writing feedback and helping P-Cubed students in class—this is represented with the relationship $b \Rightarrow c$ in Fig. 4.1. After recounting how the group responded to The Dilemma, Carly relates it back:

> "As an LA I would never want to see someone's work just completely dismissed. If they...roll through a bunch of stuff, [and] someone [else] was just like, 'What are you doing?...We're doing it this way'... I would...have to find something...and validate both sides." – Carly

Carly relates the tact of her approach to how she might address a group of students in P-Cubed. The Dilemma is relevant to her work in P-Cubed, for in both cases she wants students to feel that their work is valued. It would be unrealistic to say feedback construction is the only aspect of the LA experience Carly considered when formulating a respond to The Dilemma, so it is no surprise that Carly includes her in-class work in this discussion. This quote is valuable in demonstrating that Carly sees connections between her LA experience and how she conducts herself in other classes. As we will show next, the way she approaches her LA duties is also strongly connected to the feedback she received when she was a student in P-Cubed.

4.4.2 How receiving feedback as a student affects Carly's approach to constructing it

Carly was student in P-Cubed two years ago, and its impression on her was indelible. In sorting out what influenced her reaction to The Dilemma, we were hoping to separate her LA experience from her student experience, but consistently Carly would bring up one when discussing the other. It would be unfair at this point to say that for her they are not intertwined. One way to see the connection is by comparing her description of what the feedback should look like with what it looked like when she was a student. When Carly constructs feedback, she has a format in mind:

> "The basic format [is]: highlight a positive, highlight something to work on, explain why this will be beneficial to them, and maybe end on a positive if it works into your feedback." – Carly

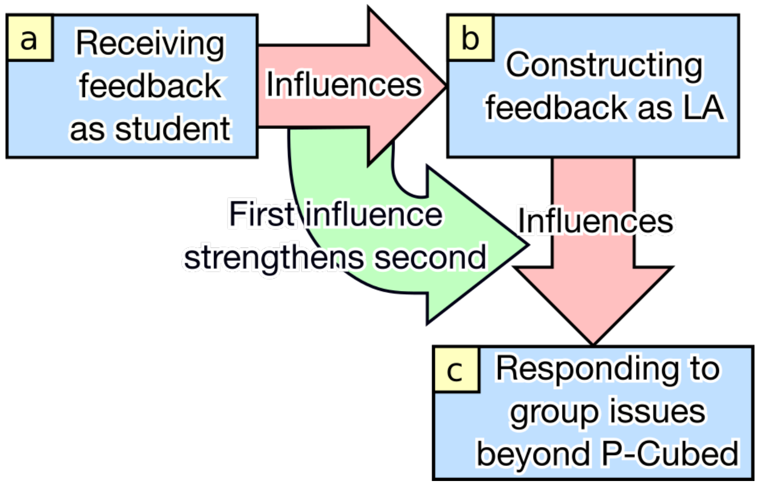

Figure 4.1: This shows direct and indirect influences of Carly's experiences with feedback in P-Cubed, as referenced in the discussion. The relationship $b \Rightarrow c$ is the focus of Section 4.4.1. Section 4.4.2 focuses on the relationship $a \Rightarrow b$. Section 4.4.3 demonstrates the relationship between the two influences, and argues that the first influence strengthens the second. The influences and connections themselves are detailed in the discussion.

She mentions three pieces: A highlight of what went well, a highlight of what to improve, and some reasoning. At other points in the interview, Carly explains that the reasoning is a justification for how the group will benefit from the improvement, and she sometimes includes an outline of steps that can be taken to achieve the improvement. When she talks about helpful feedback she received as a student, it matches up with the format she described:

> "There was one week where the positive was essentially like, 'You do a good job of facilitating discussion within the group and asking people to pause and clarify what they're saying'...but then the follow-up was, 'Sometimes though, you save questions for me as the instructor when you could be asking these questions to your group, because then that also can prompt discussion.'... For me then it was like, '...Okay, I can see this thing that I've been doing well with, and this is a way for me to continue to improve that. I've been facilitating discussion but now, like, I didn't realize that I had been saving questions just for the instructor, like I can now present those to my group as well.'" – Carly

All the pieces are there: a positive, a suggestion for improvement, and a justification. The pieces of feedback she found valuable as a student are the same pieces she tries to emulate in her own feedback. Further, all P-Cubed LAs are formally trained on how to give feedback, and the format from the training has a slightly different structure—Carly seems to have appropriated it to more closely match the feedback she received when she was a student. Seeing the parallels between the feedback she received and how she arranges feedback in her mind today, we believe that Carly's experience receiving feedback shapes how she structures it today, which is represented with the relationship $a \Rightarrow b$ in Fig. 4.1. For Carly, there is still one more layer to the couplings described between her many feedback experiences, which we will outline in the next section.

4.4.3 How the impacts of constructing and receiving feedback are connected for Carly

Carly's reflections indicate that the practice of constructing feedback influenced how she chose to respond to The Dilemma, as outlined in Section 4.4.1. Also, her experience receiving feedback as a P-Cubed student influenced the way she goes about constructing it (Section 4.4.2). In this section we will discuss the similarities in how she describes these two impacts, which make us think that the significance of receiving feedback is twofold: (1) It helped Carly develop her practice of constructing feedback ($a \Rightarrow b$ in Fig. 4.1), which we outlined above. (2) The ways she describes the two influences are so in line with each other that we believe that the first influence ($a \Rightarrow b$ in Fig. 4.1) played a role in facilitating the second ($b \Rightarrow c$ in Fig. 4.1). Perhaps the process of pulling from her experience as a P-Cubed student to develop strategies as an LA is a practice that Carly was able to refine and reuse to pull from her experience constructing feedback to develop a strategy to solve The Dilemma. This relationship between the practices is represented with the curved arrow in Fig. 4.1.

The connection between the two impacts is best displayed by starting with a piece of Carly's first quote:

> "To step back and reflect on your own group and how you're acting in that group—I think that's what...I've taken away... If I'm in a group and I'm getting frustrated, then

> it's like, 'Okay, what would I tell someone to be doing in this situation?"' – Carly

We compare Carly's explanation of how she reflects on feedback construction with a separate quote on how she decides on what to say to her students as their LA:

> "Part of [constructing feedback] is drawing on, 'Okay, what was I feeling in class at that point, what was I struggling with?' ...having been a student prior to being an LA for this class is really helpful... I think it just gives you a better understanding of the students themselves." – Carly

In both quotes, Carly is pulling from her past experience to recall how to solve a group-related issue, applying a learned lesson to the situation at hand. In the first quote, she imagines herself inspecting the group, constructing advice to help them overcome The Dilemma. In the second quote, she imagines herself as the struggling student, remembering what feedback she heard in the past that helped her overcome a similar difficulty. The reflection processes in each quote imitate each other down to the questions Carly asks herself, which exhibits that they are in some way the same process practiced twice.

4.5 Conclusions and Future Work

We now circle back to our three research questions listed at the end of Section 4.1. Our findings in relation to those questions are as follows: (1) Constructing feedback helps Carly think critically and make better decisions when faced with group-related difficulties in contexts outside of P-Cubed. (2) Receiving feedback as a P-Cubed student was an experience that shaped how Carly thinks about and constructs feedback today. (3) The process of pulling from old feedback to help her think about how to construct it [finding (2)] is a process that Carly has practiced and refined in pulling from constructing feedback to help her respond to dilemmas outside the context of P-Cubed [finding (1)]—the third finding is the connection itself.

This research highlights the positive impact, in the context of P-Cubed, of hiring LAs who have experienced the exact class they will be teaching—Carly alludes to this herself: *"having been a student prior to being an LA...is really helpful... I think it just gives you a better understanding of the students themselves."* This may seem like an obvious conclusion but this matching of LAs with their prior experiences is not always the case at institutions running physics LA programs. The degree of this positive impact could be investigated further by interviewing LAs who have taught in P-Cubed but not taken it. Currently this would describe one student. Alternatively, this finding could highlight the need to investigate further how important it is for LAs to have had prior experience in the same learning environment, especially when it is a transformed classroom with a lot of innovations.

We acknowledge that we only fully represent one LA's perspective in this paper, but the insight we were able to make into how Carly has interacted with the feedback as a P-Cubed student and as an LA makes us optimistic for the investigation that will build from this work. We expect to conduct and analyze more interviews with LAs. A preliminary analysis has been completed on one such interview, and we believe that it will showcase interesting features of the feedback's impact in the same rich, personal way that Carly's interview did.

CHAPTER 5

LEARNING ASSISTANTS AS STUDENT-PARTNERS IN INTRODUCTORY PHYSICS

This chapter represents an expansion of the research study in Chapter 4, with more learning assistants (LAs) in my data sources and considerable attention to the theory of communities of practice [62] and the model of students as partners [28]. This chapter builds on Chapter 4 incorporating more LAs into the research design, situating their perspectives within the community of LAs by attending closely to context and including the perspective of a faculty member who worked closely with the LAs in the course. This chapter also represents a development of my understanding of how research on students' perspectives can unfold, understanding that I can carry with me to subsequent research study designs. This chapter was accepted for publication and currently in press for Physical Review Physics Education Research [31].

5.1 Abstract

Despite the growing presence of student-faculty partnerships in education research and the parallels to Learning Assistant (LA) programs, there is little research done on pedagogy- and curriculum-focused partnerships that involve LAs. LAs have expertise as both teachers and learners, so why not leverage this expertise to improve the underlying structure and teaching philosophy of a course? We intend to investigate this idea in the case of Projects and Practices in Physics (P-Cubed), a flipped, introductory physics course at Michigan State University by conceptualizing its LA program as a model for LA partnerships using the Communities of Practice (CoP) framework. We found in this environment that (1) the LAs experienced a learning trajectory within P-Cubed that resembled membership in CoP, (2) the development of a specific practice among LAs resembled the evolution of practice in CoP, and (3) LAs have a strong level of influence over decision-making on curriculum and pedagogy in P-Cubed, indicating authentic LA partnership. This input is particularly important for a specific type of "students as partners": curriculum design and pedagogic consultancy, which

requires significant participation and say-so from LAs. Re-conceiving LA programs as partnership opportunities opens a path to incorporate students into and reinforce sustainable curriculum change.

5.2 Introduction and Background

The curriculum design process traditionally exists in the hands of expert instructors and practitioners, outside the influence of students themselves. Recently there has been a push to acknowledge and encourage the development of partnerships between students and instructors, where students are consulted, for example, on improving teaching practice and curricular materials. The recent focus of education research on Students as Partners (SaP) is marked by the launching of a journal dedicated to the topic as recently as 2017 [152]. SaP has been conceptualized by Healey et al [28] as a "partnership learning community" that can take on four different, overlapping forms: (1) students facilitating the learning, teaching, and assessment, (2) students conducting subject-based research and inquiry, (3) students consulting on curriculum design and pedagogy, and (4) students learning about and enhancing the quality of teaching and learning. This study will focus on a specific case of the third type of partnership—namely how a community of practice of Learning Assistants (LAs) in an introductory physics course led to a sustainable student-partnership that influenced course structures.

Typically, the work of conceptualizing partnership learning communities involves comparing them to the Communities of Practice (CoP) framework [62]. For instance, Healey et al [28] contrasted and aligned SaP with CoP. They argued that like in CoP, student-partnerships are composed of apprenticeship-like relationships where newcomers (i.e., students) learn from old-timers (e.g., faculty) by engaging in practice together. Both models emphasize a shared enterprise or goal that members of the partnership or community work towards together. The partnership also involves a learning trajectory much like in a CoP, where the student learns what goes into teaching (or other practice) behind the scenes, and comes to make their own contributions to the practice as they gain expertise and offer their own input.

That said, there is a significant difference between CoP and SaP in how members are recruited. In CoP, new members of a community join by forging relationships with existing members and aligning their participation with the goals of the community. In a partnership learning community, “it may not be enough to simply extend invitations for new partners to become part of existing communities. In these new communities all parties actively participate in the development and direction of partnership learning and working and are fully valued for the contributions they make” [28]. The contrast between who is responsible for facilitating the development of relationships in the community indicates that faculty who wish to use student-partners must be willing to work hard at forging partnerships.

Effort towards student-partnerships must also be focused. Matthews [37] highlights three tenets that make a good student-partnership. First, the relationship between teacher and student must be reciprocal, meaning all members of a partnership must give input and have their input valued. Sohr et al [29] warned against a troubling pattern where student voices get tokenized without being incorporated, so that an institution might posture at having student-partnerships in place. Second, the goals of a student-partnership must be good morally, meaning all parties benefit: faculty, students in the partnership, and other parties impacted by the partnership. Third, the outcome must strive for broad (beyond individualistic) change. For example, a partnership that changes the structure of a course in a sustainable way would achieve this outcome, whereas a temporary impact on a handful of students would not.

With these tenets in mind, SaP can still take many forms with varying levels of student involvement. To illustrate the variety, we have adopted a visualization of the “participation ladder” from Bovill and Bulley [8], as seen in Figure 5.1. The ladder was originally used to describe the relationship between students and tutors in an active learning environment, but has been repurposed [28] to describe the strength of impact in partnerships that are focused on curriculum design and pedagogy. The bottom rung of the ladder represents a curriculum that is completely in the control of the faculty member with no input from students. On the opposite end, the top rung of the ladder represents students in complete control of the curriculum. The rungs in between represent

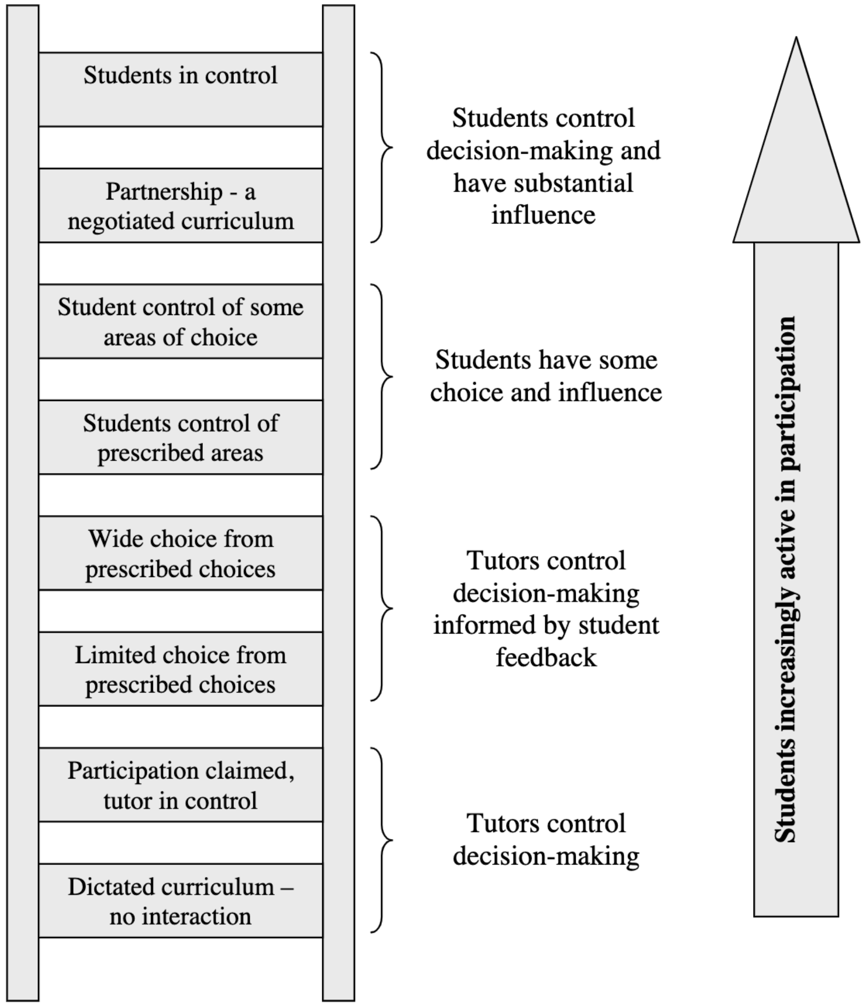

Figure 5.1: LA participation ladder: a visualization of the different levels of influence that LAs can have on curriculum design and pedagogy. Borrowed from Bovill and Bulley [8] to conceptualize student-faculty relationships instead of student-tutor relationships.

the different levels of balance between student and faculty control in the course.

The SaP literature reflects this variation. Bovill [153] emphasized that although authentic student-staff partnerships are usually high up on the ladder, "co-creation is not about giving students complete control, nor is it about staff maintaining complete control over curriculum design decisions." She argued for reciprocal roles between faculty and students, even at the top of the ladder. As an example, she described a course where the tutor/faculty guided the students in designing their evaluation exercise for the course, gathering feedback, and compiling recommendations for the course from the students themselves. In this case, the student-control over the evaluation process places this partnership on the top two rungs. Flint and O'Hara [154] described a body of student representatives who sit on university governing committees that incorporate the voice of students into institutional decision-making. Because of the history of newer student members outnumbering other students in the governing body, the students tended to have limited influence on what the committees oversaw, placing this partnership on the third or fourth rung from the top. Sohr et al [29] described students who were recruited and interviewed to help redesign a quantum mechanics class. Due to the tutor facilitation of meetings where students gave input, and the tutor-led synthesizing of feedback, this partnership would likely exist on the fifth or sixth rung of the ladder, based on the iteration described in the research. Mercer-Mapstone et al [32] reviewed and analyzed 58 papers on SaP to show that most of these partnerships focused on changing curricular materials in a course or altering teaching strategy. These partnerships were often forged informally by professors who wished to incorporate student perspectives but did not have the means to do so outside of asking students to meet with them and provide their input. From these examples, the reality of researched partnerships is that they tend to center students who do not teach and who operate within small-scale, unpaid partnerships.

An alternate model for utilizing students in the classroom is the LA model. Over the last two decades, LA programs have become an ever-growing feature in undergraduate programs across the country, particularly in STEM disciplines. Initially conceived at the University of Colorado Boulder in 2003 [96], LA programs have since spread widely in varying forms [96, 97, 98, 99, 155]. The premise behind an LA program is to hire undergraduate students as LAs to facilitate learning in the classroom. The common goals of LA programs revolve around improving undergraduate courses, helping LAs improve their teaching practices, and recruiting undergraduates into the teaching profession. While these goals are distinct from those of student-partnerships, there are some overlaps, especially in trying to improve undergraduate courses. In most of the LA programs that have been discussed in prior research, LAs fulfill three duties: teaching students in a class, attending meetings for class preparation and planning, and taking a pedagogy course or teaching seminar with other LAs [34, 100, 101, 96, 98, 99, 155]. Within physics, many active learning curricula, including SCALE-UP [156], University Modeling Instruction [157], Interactive Science Learning Environment (ISLE) [158], and Washington Tutorials [159], have been implemented in conjunction with LA programs to facilitate small group discussions and learning at the scale required for university courses.

Previous research on LAs tends to focus on the benefit LAs bring to student engagement and learning rather than to structural components of the course. For example, the presence of LAs in STEM courses has been shown to improve student learning gains on conceptual inventories [96]. The same study demonstrated that LAs also improved students' attitudinal gains compared to non-LA courses, and they increased the instructors' attention to student learning while planning for class. An extensive study [102] on instructor effectiveness—a quantitative measurement of collective student learning ascribed to instructors over multiple semesters—found that LAs helped instructors maintain their effectiveness, whereas, without LAs, the instruction declined from year to year (even when controlling for flipped- vs. lecture-style and previous teaching experience). Several studies have confirmed the benefit that LAs have on the grades and passing rates in student performance within the same courses [160, 161, 98], and in some cases especially for students from underrepresented backgrounds [162]. Thus, there are strong motivations from research to include LAs in the classroom, from improving student learning outcomes to improving teaching effectiveness.

Despite the growing presence of SaP in education research and the overlap of goals with LA programs, there is little research done on student-partnerships that involve LAs (LA-faculty partnerships). Jardine [30] researched LA-faculty relationships in undergraduate biology courses, where LAs were asked for feedback on course structures by the faculty members during meetings. The goals of these questions were to redirect how course materials were drafted up and how exams are graded, all ultimately at the discretion of the faculty. This reduced the amount of influence held by LAs since the only mechanism for change was filtered through the faculty members. Other studies highlighted LA-faculty relationships but did not analyze with a partnership lens. Sabella et al [34] demonstrated how LAs were used in a physics course to shape and improve curricular materials on a semester-by-semester basis, but they did not use the SaP framework or extend to broad, sustainable change to the course as outlined by Matthews [37]. Other research on the impact of the LA experience on the LAs themselves [100, 101, 163, 164] highlights how LAs grow as people during the experience. For example, Close et al [99] described how these LAs' identities shifted during their time as LAs using the CoP framework. However, that work focused on the individual LAs and did not detail the impact of the LA-faculty partnerships on the course structure. In some studies [163, 164], the impact was described on the basis of how the faculty member benefited from working with LAs, but again the influence did not seem to extend beyond the individuals directly involved.

This previous research highlights a disconnect between CoP, SaP, and LA programs. However, it also offers the opportunity to reimagine LA programs at that intersection. We propose that LAs in P-Cubed effectively occupy the "student" role in SaP, taking precedent from Jardine [30]. Undergraduate LAs have expertise as both teachers and experienced students, so why not leverage this expertise to improve the underlying structure and teaching philosophy of future offerings of the course? Through this study, we intend to contribute to this idea by conceptualizing a specific LA program as a model for enacting SaP using the CoP framework. In the following subsection, we outline the course context for the specific LA program.

5.2.1 P-Cubed

In examining an LA program with a student-partnership lens, we focus this study on one group of LAs at Michigan State University (MSU) who work in a flipped, introductory, calculus-based mechanics course offered in the Physics and Astronomy Department called Projects and Practices in Physics (P-Cubed) [63]. Almost all LAs in P-Cubed have applied and been hired to the teaching staff after taking the course as a student. Though they are not P-Cubed students anymore, they are undergraduates, and they have a proximity to the P-Cubed student experience that other instructors do not. LAs for the course have three primary obligations: (1) facilitate in-class group work and problem-solving by acting as a tutor who guides but does not give answers, (2) attend pre- and post-class meetings to prepare for class and reflect on how it went, and (3) write individualized, weekly feedback aimed at improving students' scientific practices. The third duty listed is different from many other LA programs that research has covered in the past, which often do not have an individualized written feedback component.

The problem-based design of P-Cubed means that students review material outside class and solve small-scale problems for homework. When they come to class, students are arranged in groups of four or five, and together they solve a single open-ended physics project that takes two hours to work through. Projects are designed to give students exposure to scientific practices [24, 63] like developing models, analyzing data, or arguing with evidence. Projects may ask students to create a physical model for a situation where a new physics concept is at play, and subsequent parts of the project may add complexity or require computational modeling. For example, one of the projects asks students to model relative motion of hovercrafts with the goal of pulling off a rescue mission for the occupants of the "runaway hovercraft." The project builds in complexity by introducing freefall and adds a computational component by having the students create a computational model of the chase and freefall in order to communicate their findings. The projects tend to focus on analysis and computation as tools for investigating physical phenomena, but experimentation is not part of the course.

Each group of students has an undergraduate LA or other instructor assigned to it (75-80% of the instructional staff is LAs), with each instructor responsible for 2-3 groups of students. The instructor's role is to guide the problem-solving process and to encourage collaboration and creativity, as there are many ways to solve each project. During class, the instructors also make observations for each of their students, which then can be used to construct feedback each week. This written feedback allows the group's instructor to reflect outside of class, address any issues from the class, and make suggestions for improvement in the next week. Instead of grading each problem for correctness, students are graded on their approach, process, and collaboration with their group. In a given week, LAs attend two pre-class meetings to prepare for each class period's physics project and one post-class meeting after both class periods to reflect on the week together and trade advice on teaching and/or writing feedback.

The P-Cubed course has several features that make it an ideal context for our investigation. First and foremost, the course was originally designed from a CoP perspective [63, 165]. When the course was conceived, the developers decided to focus the goals of the course on developing certain practices aligned with the communities of undergrad physicists and engineers, who were most likely to represent the students in P-Cubed. To make these practices authentic, the designers intentionally made the problems ill-structured and under-defined so that students would be forced to engage in solving these problems using authentic means. This means students would have to negotiate the meaning of the problem and tackle complex and intricate issues collaboratively, which in turn facilitates engagement in multiple scientific practices. While it is unclear how to design a community of practice from the ground up explicitly, it is possible to create structures and opportunities that would allow a community of practice to develop [166] among students and instructors. Second, as a part of the CoP design, LAs were intentionally positioned as intermediate members of the community of practice by the course developers [165]. Because LAs are simultaneously positioned as both peers and experts, they offer a pathway into the center of the P-Cubed community. LAs are a living bridge between the student experience and the instructor experience, representing the learning trajectory that members of a CoP can travel to achieve centrality. This trajectory was designed to be a guided experience through the use of the P-Cubed feedback mechanism (a direct link for students to learn from more central members of the community). When we examine LAs using an SaP lens, we view LAs as occupying the "student" end of the partnership, for we intend to show how LAs influence the course from positions of less power than faculty, taking precedent from Jardine [30].

Our first goal then for this paper is to demonstrate that a community of practice has indeed formed among LAs in the P-Cubed course. Though the broadest community of practice in P-Cubed would encompass all students and instructors, as Irving et al [165] proposed, we focus mainly on the community of LAs. To be clear, classrooms can develop sub-communities within the larger community, such as a small group of students, or the LAs, or the entire teaching staff including

TAs and faculty. Demonstrating existence is an important first step since a community of practice (of LAs) is not a guaranteed outcome based solely on design decisions. From there, we will show how LAs have directed and influenced one particular practice in the course—namely constructing feedback. We choose to focus on feedback rather than other practices for three main reasons: (1) The practice of feedback is outlined and described in detail in the course materials which were written upon inception of the course. This makes it easier to discuss how the LA practice of feedback has evolved over time and taken shape based on LA experiences combined with the original course design. (2) Due to the regular nature of feedback-writing and the ease with which LAs can share their written feedback among one another, it is a practice on which LAs tend to advise one another more heavily compared to other practices. (3) Feedback is an opportunity for LAs to infuse their own expertise into the course because LAs have the freedom to write about what *they* deem important to succeeding in P-Cubed. They also get to decide what it means to write good feedback when they advise one another on feedback-writing throughout the semester. For these reasons, the practice of constructing feedback exemplifies the community aspect of LA duties and the trajectory that practice can take when under the influence of central members of the LA community of practice.

Our second goal is to show how the LA community of practice can be viewed as a student-partnership in the course. This is a unique perspective and adds to the SaP literature because of the unique *trajectory* LAs take within the P-Cubed community and the *opportunities* they have to infuse their expertise into the P-Cubed curriculum. Their trajectories are special because P-Cubed LAs are recruited when they are students in the course, so they have past experience as P-Cubed students yet hold roles as undergraduate instructors.

To that end, we aim to answer the following research questions in this paper: (1) Has a community of practice developed around LAs in P-Cubed? (2) How has the practice of feedback been shaped by P-Cubed LAs? (3) How can the LAs' influence be characterized as a student-partnership, and what characterizes this partnership and its outputs?

To answer these questions, we will first dive into the details of what comprises a community of practice and how the LAs in P-Cubed could be viewed and analyzed from this perspective in Section 5.3. We will then describe our case study approach to the LA community and how this approach helped us select and analyze our data sources in Sections 5.4 and 5.5. In Section 5.6, we will present the results of the case study and answer the research questions above. In Section 5.7, we will discuss the implications of having an LA model that begins with a CoP design and has developed into a community-based partnership.

5.3 Theoretical Framework

We use the theory of CoP [62] throughout this paper to describe and analyze the community of P-Cubed LAs. By definition, a community of practice is a group of people who share common goals and work together using shared practices to achieve them. The goals are communally negotiated and evolve over time. Practices are patterns of activity that have been agreed upon over time and developed as cultural norms among the group. Learning in a community of practice happens when a member comes to participate in ways aligned with the shared practices and shared goals of the community. Historically the "center" of the community, or the goals and practices to which new members align their participation, shifts as central members leave (reduce participation) and new members join and negotiate their participation in relation to their own experiences and personal histories. We intend to use this theory of participation and learning to demonstrate that the LAs have formed a community of practice and how that community of LAs took up the specific practice of feedback-writing, made it their own, and wielded influence over other aspects of the course in a partnership-like way. In the following subsections, we introduce CoP as laid out by Wenger [62] and then show how we conceptualize the design of P-Cubed as an environment that encourages the development of a community of practice.

5.3.1 Communities of Practice

Etienne Wenger developed the learning theory of CoP [62] as a follow-up to Jean Lave and Etienne Wenger's Situated Learning [167], which expanded on the apprenticeship model to address the idea of learning as legitimate peripheral participation. In CoP, Wenger drew primarily from Situated Learning but provided more details on what it means to learn in a community of practice and framed learning in terms of a duality between practice and identity. For this study, we focus primarily on Wenger's conception of *practice*, which he viewed in terms of five mutually defining and deeply connected features: negotiation of meaning, community, learning, boundary, and locality.

Negotiation of meaning takes place in the duality of two member-driven processes: participation and reification. Members *participate* in practice by directly engaging with other members and actively carrying out the goals of the community. This participation ties to how they *reify*, or "[give] form to experience by producing objects that congeal this experience into 'thingness' " (p. 58) [62]. We can see the interlocked nature of these two processes when considering how reification is brought about by historical patterns of participation. For example, physicists often draw a free body diagram to help visualize the forces at play in an introductory mechanics problem. The setup of the diagram is not by nature a representation of forces. However, it is widely interpreted that the simplified free body and the straight arrows represent forces because of how participation patterns over time in introductory mechanics have reified forces on an object into a free body diagram. As Wenger puts it, "what is said, represented, or otherwise brought into focus always assumes a history of participation as a context for its interpretation. In turn, participation always organizes itself around reification because it always involves artifacts, words, and concepts that allow it to proceed" (p. 67) [62].

Community refers to the members themselves and their relationships with one another [62]. It also refers to their relationship with the context of the shared practice. A community consists of three dimensions: mutual engagement, joint enterprise, and shared repertoire. *Mutual engagement* in a community is marked by the togetherness of the practice and the relationships that exist between members. Meaning is negotiated between members, not on an individual basis. *Joint enterprise* in a community exists because members have mutual accountability to one another in carrying out the practice in a way that advances the cause of the community. The enterprise is joint in that it is mutually constructed and agreed upon together. *Shared repertoire* is (1) the set of routines, tools, words, actions, or concepts that the community has reified over time and (2) the ways through which these resources become a part of how community members engage in practice. We connect these three dimensions through their mutual involvement in how members negotiate meaning. For example, on a volleyball team, members need to interact constantly (mutually engage) in order to convey where the ball should be hit and who should prepare to return the ball to the other side. There may be compromises between varying interpretations of goals (joint enterprise)—some members want to have fun while others focus more on winning. Even among these goals, there are varying interpretations of how to achieve them. The shared resources (repertoire) of the team can help facilitate pursuits of the enterprise and the gameplay such as recognizable shouts of "mine!" between players to signal intent, techniques for setting the ball in a desirable spot, or announcements of the score before each serve.

Learning refers to a trajectory that involves aspects of both negotiation of meaning *and* community [62]. Members of the community traverse the trajectory by participating and reifying as described above. When members participate, they remember and forget aspects of the experience, and their memories change over time to embody how they view the relevant practice. In the same way, they reify artifacts when they participate, and these artifacts preserve the history of practices. Because of the choices that are embedded in reification and the selectiveness of memories, members come to view practices in new ways and they gain experience with *doing* practices in such ways. The practices themselves can change too, as more central members develop new perceptions and ways of doing things based on the choices packed into reification and memory. This process defines learning. Newcomers to the community invariably must learn the practices, and they embark on this trajectory by participating (forming selective memories) and reifying (preserving their participation). Importantly, this is a community process, because newcomers would not know how to participate without mutual engagement, and they would not know how to reify without a shared repertoire that they can dip into. As they move closer to the center from the periphery, their practice transitions from learning from others to learning where the practices of the community are headed (and influencing their direction).

Boundary emphasizes the ways that participation and reification can connect communities and create a sense of continuity between their practices [62]. Members of multiple communities can act as *brokers* by translating elements of practice across contexts through their participation in those communities. The focus lies with *participation* of brokers because of the active role brokers play in understanding how practices are connected and introducing and facilitating modes of participation from one community to another. An example of a broker is a high school track coach who draws on her experiences networking with other coaches at track meets to teach running techniques to her student-athletes, thereby relaying participation from her coaching community to her high school track team community. Reification can also serve as a robust inter-community connection, which Wenger described using the term *boundary object*. We often refer to instances of reification as "objects", but when they belong to multiple practices, "they are a nexus of perspectives and thus carry the potential of becoming boundary objects if those perspectives need to be coordinated" (pp. 107-108) [62]. For example, the act of making possible and enabling the production and distribution of a band's music could be reified in a recording studio, but that studio is also used as a place of work for sound engineers and technicians. The studio is a boundary object because these different communities (band members, technicians) use it to come together and coordinate their perspectives and practices.

Locality refers to the size and scope of a community of practice, especially in relation to larger communities to which it belongs or smaller communities that it comprises. Multiple communities of practices can sometimes be viewed as a "constellation" [62] of communities. This is meant to evoke the image of communities grouped together by some measure of proximity, common participants, or patterns in practice. The proximity of communities in a constellation can be officially reified, in the case of a unified league of sports teams, or unstated, in the case of informal groupings of skaters that may show up at the skatepark at given time. In the more structured communities, one can even identify sub-communities and overlapping communities that exist simultaneously within a constellation. For example, in a soccer team, there is a community of all players, a community of midfielders, a community of coaches, a community of defenders and defensive coaches, and a community of the entire team. The list could go on given the myriad skills and gatherings that are important to the team. Each sub-community evokes a different level of locality. Together they form a cohesive community and its practices, practices that reflect and refract the practices of the sub-communities.

5.3.2 The design behind the development of a community of practice in P-Cubed

In thinking about how the burgeoning community of LAs in P-Cubed could embody the features of a community of practice, it is helpful to discuss how negotiation of meaning, community, learning, boundary, and locality are designed into the course. For the purposes of this paper, we will focus our examples on the practice of writing feedback; however, we recognize that this process could also occur for the other practices designed into the course. First, we will address the negotiation of meaning, which, at its core, is the duality of participation and reification. When we think of how LAs are meant to engage in participation, we envision discussions that are encouraged during post-class meetings about how to address student behaviors in feedback, interactions with students in the class, and the processing of LA-jotted in-class notes into the feedback itself. When we think of how LAs are meant to engage in reification, we envision how they use the assessment guide in deciding how to frame their feedback. Phrases like "group understanding" (the title of an in-class assessment category) can be used to communicate to students and other LAs about in-class observations. LAs also need to interpret whiteboard scrawlings during class to understand where their students got stuck. The ways that LAs are meant to participate and reify in their feedback-writing practice are necessarily interlocked, and these processes together are how LAs negotiate meaning—without them there would be no point in writing the feedback, and its contents would not be meaningful to the students if not based on in-class observations and LA-written notes. When extended out to other practices that LAs could have influence on, we look at negotiation of meaning from an SaP perspective, which puts lasting, structural impact into focus. This highlights that structural influence often takes the shape of reification, a process that produces artifacts for future community members to shape their own practice around.

The LA program in P-Cubed is also designed to form a community (the second feature of practice). We envision mutual engagement among LAs in discussions between LAs on feedback-writing during post-class meetings, relationship-building through shared coursework and studenthood, and the helping-out that happens when LAs ask one another to review their written feedback. For LAs who write feedback, the joint enterprise would be focused on the goal of helping students improve their scientific practices and group work through the process of writing individualized feedback for them. The reasons for LAs to review one another's feedback would include not only the relationships that exist between LAs but also their understanding that the improvement of any LA's feedback is an advancement of the joint enterprise. The shared repertoire of feedback-writing includes in-class note-taking, the act of writing the feedback itself, the norms of interaction during post-class meetings, and the shared historical experience of having been a student in P-Cubed. Because the design of P-Cubed encourages the collective experience described, we aim to explore how LAs can have a powerful collective impact within the potential student-partnership that we will investigate.

Third, the learning trajectories of LAs and of the community itself ideally begin when future LAs are students in the class. The P-Cubed feedback and in-class teaching practices are meant to onboard students with collaborative skills and an understanding of what it takes to be an LA. Students who are recruited into the LA program would be positioned as "newcomers" in the community. Newcomers learn by aligning their participation with more senior members of the community, which in the case of P-Cubed would mean that LAs would collaborate by consulting one another on feedback and by asking one another for help teaching during class when issues arise. As LAs gain teaching expertise and travel along their own learning trajectory, they would also start to gain influence over the direction of the practice. Over time, practices would evolve similar to how we would envision the impact of a student-partnership. Learning trajectories are where we would look to in order to examine whether the SaP model can be applied to P-Cubed.

Fourth, the boundary of the P-Cubed LA community can be illuminated by its brokers and boundary objects. LAs could act as brokers by drawing on outside experience to bolster their teaching and feedback practice—some LAs would have received vivid and helpful feedback when they were students in P-Cubed, which they might translate into constructing feedback today. Others study physics or engineering in upper-level classes, from which they can draw to provide a more in-depth perspective on some of the physics concepts for their students. An example of a boundary object is old feedback that an LA received as a student in the past. When they first received it, it served to help them improve their scientific practices and group work, which advanced their learning as a P-Cubed student. Now, as a P-Cubed LA, they can repurpose the old feedback to help them understand what could be helpful for a current student to hear. Even though the LA's involvements in each community are separated by time, the boundary object (old feedback) reified past participation (e.g., group work) in a way that has allowed the LA to access and translate it for use in the current practice of feedback construction. This exemplifies one of the ways LAs have personal influence on P-Cubed practices, which could be viewed as an instance of LAs leveraging their power in an LA-faculty partnership.

Lastly, the locality of practice is also relevant, though mostly for clarifying how we use language in this investigation. To summarize its presence in the design of P-Cubed, *locality* refers to the unit of analysis of the community of practice. We could have expanded the scope (locality) of our investigation to focus on the entire class of LAs and students, or we could have narrowed to a small group of LAs that meet for pre-class meetings together. We chose to view the LAs as a single community or "unit" because this is what allows us to most easily discuss the varied perspectives of LAs and how those perspectives trace their roots and evolve. However, this community exists within the community of teaching staff (including TAs and faculty), which exists within the even broader community of P-Cubed students and teaching staff combined. We will sometimes discuss these other communities in our study, because movements and practices within the community of LAs can sometimes reflect movements within the teaching staff or the whole class, especially when conceptualizing the LA-faculty partnership.

5.4 Methodology

By focusing on the LA and faculty perspectives in this work, we choose to take up an interpretivist lens [50] on the case study. This means we adhere to the idea that we use case studies for seeing how participants socially construct a phenomenon and what it means to them as participants. In this investigation, the phenomena encompass the relationships between instructors (LA-to-LA and LA-to-faculty) and the relationships between LAs and teaching practices. The case itself is the P-Cubed environment. The interpretivist stance is helpful for our study because it helps us leverage the participants' perspectives on the phenomena, which are centered around LAs and their function—what matters to us is not the essence of P-Cubed's LA program (if there even exists such a distillation), but rather how LAs experience it.

We chose to generate most of our data from interviews with LAs and a faculty instructor. The reason for this is that we treat each interview as a separate "anchor point" [50] from which we can view the phenomena of interest. We use this terminology because the interviews serve as anchors which ground the phenomenon, because the interpretations of participants are what give meaning to the phenomenon. By accessing multiple "anchors," or interpretations, we will examine participants' language to build our own understanding of the LAs' perceptions of the phenomenon. We describe the interviews and other data sources in greater detail in Section 5.5. Our interpretivist stance motivated us to choose data sources that represented the LA/faculty perspectives on the communities within P-Cubed, of which they are members.

In a prior study [60] on LA feedback in P-Cubed, we focused on how LAs transferred practices and skills from their experience in feedback construction to other academic settings. A main finding for one LA was that the feedback mechanism played a big role in making her LA experience meaningful, as well as helping her manage her academic studies in other contexts. The depth of the relationship between the feedback mechanism and this LA's academic life pointed to the boundary-crossing that happens when LAs learn to use their teaching expertise in other areas of their lives. This process is part of what happens in and out of a community of practice, and our research questions in this investigation focus on characterizing the LA community of practice, highlighting how LAs have impacted the practice of writing feedback, and understanding how the LA-centered partnership is reflected in other P-Cubed processes.

We chose to bound our case to the experiences made known to us through interviews, emails, and written course artifacts like feedback and course materials, because we sought to compare the experiences and artifacts that most closely related to the feedback construction process. These glimpses into the lives of LAs and instructors gave us a unique view into the functioning of P-Cubed's teaching staff that only the practitioners could give. By investigating how a feedback mechanism like the one in P-Cubed functions in the hands of LAs, we intend to demonstrate how the practice of constructing feedback has developed under the influence of LAs, and how that influence points to the dual existence of an LA community of practice and a student-partnership between LAs and faculty. When LAs allowed us to step into their world to see what they value and practice as a community, we were able to demonstrate what this community of practice and partnership looks like and how it functions.

5.5 Methods

Our analysis focuses on interviews with three P-Cubed LAs as the primary data source. We also sought alternate angles on the feedback mechanism by gathering written feedback excerpts from the interviewed LAs to cross-reference with their interview comments, interviewing a P-Cubed teaching faculty member, and collecting artifacts from the semiannual LA training where new and old LAs convene to be trained by Irving and McPadden on constructing feedback, among other things. We display the complete set of data in Table 5.1. We found that the LA interviews provided the most profound insights, which is reflected in how we showcase our analysis.

We conducted interviews in a semi-structured manner. The original protocol was developed

Data Sources	
Individual interviews	Four semi-structured interviews: three with LAs; one with faculty
Feedback	Forty written feedbacks from each LA (120 total)
Course documents	Assessment guide; Presentation from training
Notes	One set of notes jotted during LA group discussion during training
Emails	Written email correspondence with two LAs after interviews

Table 5.1: Five types of data sources: interviews, feedback, course documents, discussion notes, and emails.

using Patton's methods [45] to address earlier research questions about how the feedback mechanism influenced LAs' academic lives. As the angle of our research shifted in response to interview comments, so too did the interview protocol. In this way, we developed the protocol iteratively. The artifacts and feedback excerpts were gathered directly from LA training and the course archives. When the focus of this case study became the influence LAs wield upon P-Cubed teaching practices, we generated additional data. First, we gathered email exchanges with the interviewed LAs where they described how their roles changed over the course of their LA tenure. Second, we interviewed a faculty member—Roland—to discuss how he had worked together with the LAs and leveraged their expertise in a variety of ways. Roland has taught P-Cubed several times but was not involved in its original curriculum development.

We interviewed three LAs for the investigation presented here, though the three we focus on were selected among five interviews. We chose these three LAs because they portrayed the deepest reflection on their experiences and were able to articulate their relationships with the feedback mechanism with nuance and clarity. We attribute this distinction in part to the iterative development of the interview protocol, which did not give the first two interviewees (Alvin and Bella) as much of an opportunity to discuss their feedback writing. The latter three (Carly, Derek, and Erica) were also all seasoned LAs with multiple semesters of teaching experience to reflect on, which has provided them with multiple, variegated perspectives on what the feedback means to them and how they have helped the mechanism develop over time.

For these reasons we present the perspectives of Carly, Derek, and Erica. Carly is a biosystems engineering major, who at the time of her interview was finishing up her fifth semester as an LA. Derek was an LA for seven semesters, and he recently graduated and entered the workforce as a mechanical engineer at a large manufacturing company. Erica is a physics major who was a P-Cubed LA for four semesters and, at the time, was finishing up her second semester as an Electricity and Magnetism P-Cubed (EMP-Cubed) LA. All three LAs are white, as is Roland. We treat the interviews as individual anchor points [50] through which we can understand how LAs came to perceive and influence the feedback mechanism during their time in P-Cubed.

5.6 Analysis and Findings

Our research questions were asking: (1) Has a community of practice developed around LAs in P-Cubed? (2) How has the practice of feedback been shaped by P-Cubed LAs? (3) How can the LAs' influence be characterized as a student-partnership and what characterizes this partnership and its outputs? In this section we will outline our findings with respect to this focus. First, we will demonstrate how the LAs comprise a community through which new LAs can learn from older ones and master teaching practices (specifically feedback) that P-Cubed LAs have taken ownership over. Second, we will show how the LAs have taken ownership over the practice of feedback-writing and developed and changed it in a way that is aligned with LA-held values and experiences. Third, we will show how the LAs have come to occupy influential positions within the P-Cubed instructional staff and how they have forged an effective partnership with faculty in a way that gives them influence on how the course is run beyond just normal LA duties.

5.6.1 The Learning Assistant community of practice

The first main finding was that the LAs experienced a learning trajectory within P-Cubed that resembled attainment of central membership in CoP. Specifically, we found that LAs make up a community in which new LAs learn from older ones and hone their teaching skills, eventually taking on the roles of veteran LAs in a cyclic fashion. In Section 5.2, we demonstrated how the design of the course was primed for a community of practice to develop, and here we will show that one has indeed developed among the LAs. Since design decisions do not guarantee the development of a community of practice, this finding serves as evidence that the design principles in P-Cubed [165] did in fact lead to a community of practice developing among the LAs in the course. The LAs share the joint enterprise of teaching this course, along with a shared repertoire of course materials, problems, experiences, and training. Additionally LAs are continuously engaging with one another (mutual engagement) through weekly pre- and post-class meetings. More importantly, we see that LAs experience a learning trajectory in the community. This process, as we will demonstrate, begins with being a student in the class, and develops over time as a student is recruited into becoming an LA, and as that LA learns to hone their practice and exert their own influence and perspective on how the course is run.

When we interviewed Roland about his teaching experience with LAs, he described this process in detail. He started by talking about what it's like for new LAs to adjust, which is an important step that new members of a CoP go through when learning to take up practices at first.

> "They come in and they worry about a lot of things. And they can then consult somebody who isn't, some guy that's like their dad's age or older. They can talk to somebody who's their peer about strategies for going through things. I mean, it's one thing for me to tell them...it's another thing to have somebody who they see as their peer say, 'you know, this actually does work if we try this'...not necessarily how I'd want to approach an issue, but [the older LA] might have tried things that might have worked better for them." (Roland Interview)

He first talked about how it's easier for new LAs to learn from and consult other LAs as opposed to Roland himself, who said he's probably older than their dads. He highlighted this connection between peers that might be more automatic and comfortable for these newer LAs, which puts the older LAs in a perfect position to provide initial guidance into what it means to teach as a P-Cubed LA. This is aligned with the CoP idea that newcomers learn best from more senior members of the same community [62]. Roland also mentioned how LAs might provide suggestions that don't necessarily match up with how Roland would "approach an issue", but he acknowledges that this is a plus, because veteran LAs will have ideas about what worked for *them*, to which a newer LA would likely relate much better than they would to Roland. This is also in line with the idea that LAs learn from other LAs in the P-Cubed LA community of practice.

Roland also talked about how he noticed LAs helping each other out in a variety of settings, like meetings and outside of school. One skill he said LAs learn is how to help each other out with teaching duties. He commented on the disproportionate benefit it made when older LAs exemplified this skill as opposed to Roland simply articulating it.

> "I'd try saying this, 'Try relying on your, your fellow LAs.' But when you have senior LAs...who were so willing to do this and so willing to go out of their way and help the other LAs in the class, it was contagious." (Roland Interview)

Roland highlights how the senior LAs model the behaviors that he wants to suggest to the new LAs, and by doing so, they set the norms for the group. Though he was a member of the larger teaching staff community, Roland witnessed these behaviors from outside of the tight knit LA community. It was almost as if Roland's mentoring duties as the faculty instructor were superseded by the "contagious" behavior of veteran LAs who already exemplified what Roland hoped the new LAs would learn to do. Rather than Roland teaching the new LAs, it was the LAs who taught one another the practices of their LA community. Again, we see older LAs guiding the learning trajectory of community newcomers and how LAs are able to mutually engage as a community.

The LAs themselves were also aware of their central role in maintaining the community of LAs and their take-up of teaching practices. In reflecting on this process via email correspondence, Erica provided an example of what this community process looks like on an everyday basis. In Figure 5.2, we show a screenshot that Erica took of a conversation with a fellow TA about how to polish a feedback to be given to P-Cubed students. This occurred after Erica had been teaching for seven semesters (as an LA, and newly as a TA) and her peer was a first-semester newcomer to the teaching staff, which means this interaction offers a snapshot of the community that exists across instructors with varying levels of experience. Though not an interaction from within the LA community, this example serves as an insight into the LA-adjacent parts of the teaching staff community, which are refracted into the LA community through the concept of locality.

In the exchange, Erica, writing in the blue text bubbles on the right-hand side, provided some lighthearted comments about how to reword several sentences that the other TA (words in grey on the left) had sought her advice on. It is obviously a friendly exchange as there are many exclamation marks, laughter typed out in all caps, and use of emojis throughout the message. Erica and this other instructor clearly have an easy rapport both as friends and fellow teachers. This provides insight into what relationships between student-instructors can look like in the P-Cubed community. As evidenced by the personal text message, the connections between instructors go beyond classroom exchanges, and many see one another as friends and confidants. From a CoP perspective, this extends the boundaries of the teaching staff community, and allows its members more opportunities and places to share practices and help one another improve, such as through texting.

When we compared the feedback written by LAs with the perspectives they provided in interviews, we found confirmation that the LAs accumulated expertise as they moved up through the P-Cubed LA community. In Carly's interview, she recalled how feedback she had received as a student in P-Cubed helped her maintain confidence as she went through the course for the first time. Specifically, she highlighted how *balance* can be helpful by talking about how criticism can be connected to praise in ways that made it easy for Carly to see how she could improve.

> "One thing that I found—I think that I usually found the most helpful was when the positive thing that was being highlighted was connected as well to the thing that I

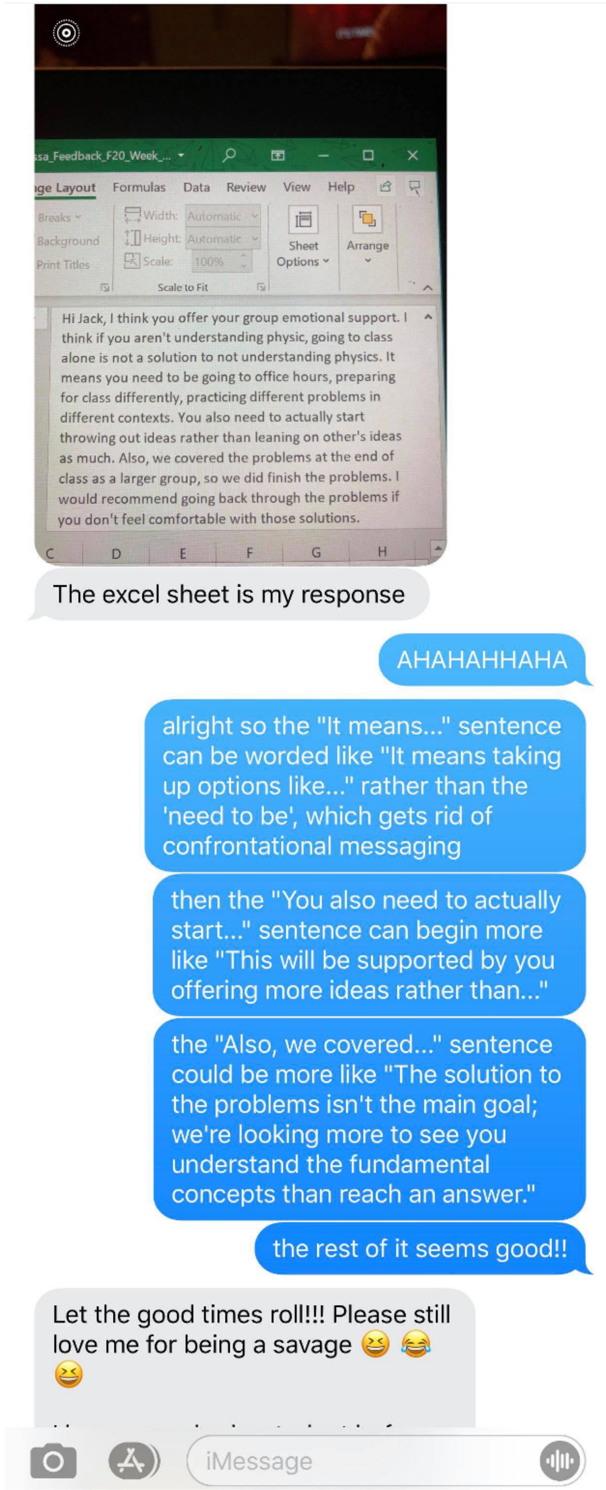

Figure 5.2: Text exchange between Erica and a TA, exemplifying strong relationships within the student teaching staff of P-Cubed. The blue bubbles on the right show Erica's suggestions for the TA's feedback, while the grey bubble on the left shows the TA's response to Erica's suggestions.

> needed to improve on, because then that gave me a clearer idea going into class of, 'okay this is one thing that I'm going to focus on today.' " (Carly Interview)

The reason we bring up this experience is because it demonstrates how Carly was thinking about what was and was not helpful about the feedback from an early point in her LA trajectory, even before she began constructing feedback herself. By design, new LAs are recruited from the set of current and former P-Cubed students in part so that they can draw from experiences such as these. Carly's experience is proof that the learning trajectory of LAs can begin when they are still students. Specifically, she was learning to construct feedback even before she became an LA, which indicates that non-LA students can exist on the periphery of the P-Cubed LA community just like Carly did.

In reading through excerpts of feedback written by Carly, we found several instances of balancing praise and criticism. One instance is provided below.

> "You showed a lot of initiative and did a good job of getting the group started on working on the problem. I liked that you were thinking out loud and talking through your work as you did it. However, there were several times where the entire group was not on the same page or were not fully understanding what you were working on."
> (Carly Feedback)

Here, Carly pointed out that the student was promoting work within the group, which was good, but the group members did not have a strong understanding, which was what needed to improve. She tied the improvement to an already somewhat productive activity that was happening within the group, thereby highlighting the connection between her praise of the group and her suggestion for improvement. Her usage of this strategy and her acknowledgement of its helpfulness in her interview show that her feedback practice is connected to her earlier experiences. This strengthens the idea that students like Carly can find themselves on the LA learning trajectory even before they are officially hired as LAs.

To show another example of what this trajectory-into-community can look like, we also demonstrate how Derek gained expertise and used it in practice. During Derek's interview, he provided a detailed look into a time when feedback helped him improve his group work and start buying into the class when he was a student in P-Cubed. The feature that he found so helpful was that the suggestions in the feedback were justified. His instructor was trying to get Derek to interact with his group more and generate discussions.

> " 'You need to incorporate discussion with your other group members, because the goal of this class is to work as a group, and you won't be able to solve the problem and you won't be able to get your understanding better unless you start conversing with those other group members.' That was at the very beginning of the class, and that helped, because once I started conversing with my other group members... it actually created a better environment in our group, kind of almost trust, like 'alright I know that you're asking this question about why I think it's this way because that's what we do in the class.' " (Derek Interview)

The instructor suggested interacting more with group members during class. What stuck with Derek was the fact that this interactive theme was aligned with the goals of the entire course. Derek used this same justification to normalize question-asking within his group, and he says this process led to "a better environment in our group." There are two main takeaways from Derek's reflection: (1) Derek learned the importance of justifying critique in feedback, which was a major step for his trajectory as a feedback-writer in the LA community. (2) He realized the importance of group work in P-Cubed, which led him to improve his *own* group work. This is a key skill among members of any community of practice, who collaborate frequently on mastering practices. Though Derek's trajectory began in the whole-class community, the skills and values he learned as a student were replicated and refined as he joined the community of LAs within the larger P-Cubed community.

In reviewing the feedback written by Derek, we saw the same commitments carried out. Below, Derek encouraged a group of students to work together instead of waiting for Derek to rescue them.

> "Listen to each other's ideas, don't just wait around for me to give you the answer because if you aren't making an attempt to work with each other, I'm not going to be much help. I know you can do this because at the end of class Tuesday everyone helped each other when I asked those individual questions. It worked out really well when you all worked together." (Derek Feedback)

Derek justified his suggestion by writing that he would not be able to give away answers, which means that the students would need to adopt a better strategy for working together. He referred to a time when this group *did* work well together, and used it to back up his reasoning in the feedback. In this example he is passing on and modeling practices that he came to value—justifying critique and working together. This is Derek's way of extending an opportunity to take up the learning trajectory that many LAs and P-Cubed students have taken before.

Another nod to Derek's high view of group work came during an interview comment when he was reflecting on what it was like to be a P-Cubed student. In particular, he found it helpful to get others involved and ask questions. These practices align well with his previous commitment to "start conversing" with his group.

> "Getting everyone involved, and asking questions... I valued those behaviors before I became an LA, because when I would not do those behaviors, I would be like, 'I'm struggling in this class right now', and when I would do those behaviors, I would go, 'This class is really easy.' " (Derek Interview)

Again, Derek discussed how he learned to conduct himself in certain ways in order to be successful—e.g. "getting everyone involved" or "asking questions." It came as no surprise to see elsewhere in Derek's feedback statements like, "take a step back and talk to your group", "ask questions about what you are missing", and "if you aren't making an attempt to work with each other, I'm not going to be much help." The suggestions he provided in his written feedback stand parallel to the behavior he adopted as a P-Cubed student and LA. Like Carly, this points to a cohesive learning trajectory that Derek followed as he learned to construct feedback as a P-Cubed

LA. Each trajectory began when they were students in P-Cubed. As Carly and Derek grew from students to LAs, practices from student-centered group work evolved into practices dear to the LA community. This dual experience points also to a shared repertoire of practice that LAs develop beginning with their time as students in P-Cubed.

We have argued that the LAs operated within a community of practice, and more specifically that they underwent a learning trajectory as they progressed from P-Cubed student, to new LA, to veteran LA. An important part of this process was the sense of togetherness, because the LAs learned through their relationships with one another and their past experiences within P-Cubed. Because of this closeness, they collaborated on many teaching efforts. Roland had a keen eye for how these communities (LAs only and whole-class) came together while he was an instructor.

> "[A senior LA] helped foster a willingness among the LAs to help each other...a willingness to say, 'let's help each other.' Because sometimes some of the other LAs might have a solution and they rely on each other like that and that was really nice." (Roland Interview)

In this comment he described how a senior LA used her relationships with the other LAs to encourage them to help one another with teaching issues or when a solution to a problem needed to be shared. From the CoP perspective, this togetherness shows how members of the LA community leveraged their relationships to build a shared repertoire of practices. In this excerpt and throughout this subsection, we see community as the source from which LAs learn to grow and improve their teaching.

Another way to conceptualize the trajectory towards central membership in the P-Cubed LA community is by considering the student body of P-Cubed as its *own* community from which a pathway leads to the LA community. Roland commented about the preparation LAs go through as past P-Cubed students.

> "They know the environment. They know the community of the class. They know how the students within groups can interact...I think it just makes for a good community of

> learners. And the LAs having done that—I think that also helps them help each other as they teach the class." (Roland Interview)

The feature he highlighted was the communal aspect of being a P-Cubed student. They learned to help each other and collaborate as students in the past. Those same collaborative practices continued to help them as they worked together on teaching the class. He went on to compare the enterprises of each community: learning science and teaching it.

> "The P-Cubed community is like, 'how do we do science?'...While science educators [are like], 'what do we do as we *teach* science?' We sort of can follow the same model: what works, what doesn't work. We collaborate with each other. And I think it does transfer." (Roland Interview)

He again highlighted the collaborative aspect of each endeavor and capped the discussion with a reiteration that he "think[s] it does transfer", meaning the LAs have transferred their model of figuring out how to *do* science into a model of how to *teach* science. From a CoP perspective, Roland is pointing to the broker-like nature of being a P-Cubed LA. Mastering science practices together as students builds co-working skills—skills that new LAs have already learned to excel at before they first stepped from studenthood into the LA position (from the whole-class community into the LA community). This sets them on a course towards the center of the LA community just like the LAs who came before. It's notable to mention here that Roland did not participate in the curriculum development process for P-Cubed, which further highlights that the class is seen as a community even by those who did not design it into the course.

Through these quotes, we have provided evidence that there is a community of practice among the P-Cubed LAs. They share the joint enterprise of helping their students develop scientific practices and group work skills, and they learned to achieve these goals by collaboratively figuring out best practices (or in CoP-speak, developing a shared repertoire through mutual engagement). The existence of this LA community is owed in part to the learning trajectory that LAs take as they move from students to senior LAs in the course.

5.6.2 Development of feedback practice

The second main finding was that the development of feedback practice among LAs resembles the evolution of practice in a community of practice. In Section 5.6.1 we established the existence of the LA community of practice and the LAs who participate. We dissected how Carly balanced praise and critique in her feedback and how Derek leaned his feedback into group work and justified his critiques. These were presented as evidence for the learning trajectories and memberships that Carly and Derek have traversed and held within the LA community. Additionally, when analyzing LA interviews and feedback excerpts, we noticed that the LAs had iterated on what feedback looked like compared to its original presentation in the course materials in subtle but important ways. In this subsection, we will show in greater detail how these LAs have developed the practice of writing feedback. This influence on a practice in the LA community exemplifies how LAs participate in negotiating a joint enterprise, which is an important part of any community of practice. It's a process that captures the trajectories of whole communities, because it indicates how a community's goals are changing.

Before we dive into what feedback has evolved into, we look to how it began. P-Cubed has been offered every semester since Fall 2014, which means it has undergone six years of iteration in its teaching. Its original developers penned a guide for constructing feedback, and one of the course's original developers and instructors (Irving) is still involved in the training of LAs. His influence through the course materials, the LA training, and the management of LAs is important when considering how the course has evolved. To see what the course materials look like, we have analyzed the assessment guide meant to be used when LAs provide grades of in-class work alongside the written feedback.

When describing how students will receive feedback, the assessment guide provides structural details that students can expect to see. Based on their in-class performance, students receive a numerical grade with written commentary that outlines something positive they did, something to work on, and a suggestion for improving their in-class work.

> "You will be provided with written feedback before the start of your next project based on your performance on the previous week's project that will focus on one type of participation that you excelled at and one area we would like you to work on in the next project and suggest how you might go about doing that." (Assessment Guide)

This same structure is rephrased during a presentation to LAs at the beginning-of-semester training. Again, we see praise, a critique, and a strategy for improvement.

> "Feedback has two parts: How did the group do? How did the individual do within the group? Each part addresses three things: (1) Something the student/group did well, (2) Something to work on for next week, (3) A strategy for how to work on it." (Training Presentation)

The training presentation further clarifies the structure of feedback; there is an explicit instruction for LAs to write feedback that addresses both the group and the individual. We refer to this portion of the feedback practice as "reified" because it is what has been baked into the materials that have withstood cycles of LAs and in part guided the take-up of LA teaching practices. We represent the feedback and its reified components (as portrayed by the instructor-designed materials) in Figure 5.3. Though this does not capture the LA perspective, it provides a starting point which will make it easier to show how the LAs elaborated and filtered the feedback mechanism in various ways. When the course was conceived, this reified feedback represents a snapshot of the original "enterprise", upon which the LAs negotiated their own goals and best practices when they wielded influence within the LA community.

To show how LAs have played a part in making feedback their own, we begin by reframing the formative experience from the previous subsection that Carly talked about in her interview. She asserted that balancing *and connecting* praise and critique was important to her when writing feedback. The emphasis on connection is not part of the reified feedback, but it was part of Carly's P-Cubed student experience. She specifically remembered receiving a piece of feedback from her time as a student that helped her come to this viewpoint.

First paragraph, to group:

a praise of in-class work
a critique of in-class work
a strategy for improvement

Second paragraph, to individual:

a praise of in-class work
a critique of in-class work
a strategy for improvement

Figure 5.3: The feedback structure described in the course materials is two similarly structured paragraphs focused on in-class work by the group and the individual.

> "There was one week where the positive was essentially like, 'You do a good job of facilitating discussion within the group and asking people to pause and clarify what they're saying'...but then the follow-up was, 'Sometimes though, you save questions for me as the instructor when you could be asking these questions to your group.' " (Carly Interview)

This clues us further into how Carly sees the balance—not just as a tally of positives and negatives, but in a connected way, where the suggestions fit in alongside things that the student is already doing well. In reading through excerpts of feedback written by Carly (when she was an LA), we found several instances of balancing and connecting praise and criticism, such as the excerpt in the previous subsection.

Another piece of feedback that Carly wrote exemplified this connective balance that she was committed to providing for her students.

> "You do a great job of working through the math problems that are involved within these problems and I can tell this is an area you are comfortable in. If I had one recommendation for you it would be to leave your work in variables for as long as possible." (Carly Feedback)

Carly used the same strategy as before. She praised a student for her proficiency with math and then suggested a further improvement to use variables more often. Carly's experience about feeling reinforced by this connective balance was reflected in how she wrote feedback. The connection between the positive and room-for-improvement aspects of the feedback was never outlined in the assessment documents or discussed in the LA training around feedback. This connection although a subtle change does significantly transform the direction of the feedback as being targeted around one theme or practice as opposed to a divergent emphasis where positive and improvement aspects are split in focus. Currently we have no way of evaluating whether a concerted focus or split emphasis will have more of an impact on the students, however, this is not the focus of this paper. Instead Carly, based on her experiences and what she believes to be beneficial, has added to the feedback approach by deciding on the need for connectivity. In this way, she was able to redirect the enterprise of the feedback practice within the LA community.

When examining Derek's and Erica's feedback, we found similar patterns despite not hearing about experiences from studenthood that reinforced this feedback-writing strategy. For example, Erica's feedback to one student highlighted his strength of putting in most of the group's effort alongside a caution that he should encourage other group members to try out their own ideas.

> "You had many equations and drawings in front of you, something that your group needed a lot. Don't let yourself be the only one doing this, however, because it seemed like your group was starting to become reliant on your work to get them through the problem...If you see yourself being the only one doing writing or calculating, stop and ask your group members what they think." (Erica Feedback)

She connected the praise—supported his group by creating physics representations in front of him—with the critique of suggesting that he encourage other group members to take the lead sometimes. If Erica learned this connection-strategy from Carly rather than from her own experience with feedback as a past P-Cubed student, then this suggests that LAs in P-Cubed are learning to write feedback from both (1) their experiences as students and (2) their collaboration with one another. Even the instructor who provided feedback to Carly years ago was diverging slightly from the explicit, reified instructions in the course materials. This suggests a gradual shift in how feedback is given in P-Cubed—the strategy of connecting and balancing was already somewhat in practice when Carly took the class based on the feedback she was given, but that strategy was never formally reified. Carly has now emphasized and centralized its importance and given her level of experience and centrality to the LA community has likely instilled it in other students and LAs. This aligns with ideas from CoP that would suggest LAs learn practices in concert with other LAs but also act as brokers who may transfer practices or values from outside the community.

A second feature of feedback practice that we analyze here is the written justification of critique. In the previous subsection, we demonstrated Derek's commitment to this practice. When we examined notes taken during a discussion among LAs at training, we noticed that older LAs tended to suggest taking up this practice, despite its absence in the course materials: "Justify why you are asking them to do something", "Make sure you mention why their grades changed if they did" (LA Discussion Notes). This focus on putting justification in the feedback is something that all interviewed LAs agreed on. The fact that it surfaced during LA training in discussions between LAs but not at all in the course materials suggests that this feature of the LA-filtered feedback has emerged primarily from experience rather than course design.

We can point to Derek's feedback excerpt in the previous subsection as a prime example of critique being justified. An explanation for this commitment could be that LAs feel that they have less authority than graduate TAs or faculty instructors, leading them to justify the feedback they give to their students as a way to build credibility. Below we showcase some examples of how Carly and Erica provided justification in a similar fashion to Derek.

For example, Carly told a student to use variables instead of numbers when doing math.

> "Leave your work in variables for as long as possible. By only putting numbers in at the very end, you will make it easier to catch simple mistakes and to add in other variables as needed. This will also help you and your group to see the connections that there are between various variables and equations." (Carly Feedback)

The suggestion Carly gave was backed up with reasoning. Carly wrote that using variables would make it easier to catch mistakes and see connections when carrying out the math. Her feedback demonstrates a commitment to telling her students why a suggestion is being given.

For Erica, too, the feedback she wrote for her students exhibited a deep commitment to providing her students with reasoning for her suggestions. Below, she wrote to her group about going through the problem-solving process a second time.

> “Take some time to explain the methods of what you’ve all done so far before I come ask. It’s beneficial to do this because sometimes, the methods you all come up with are not structurally sound or use equations that aren’t relevant. Sometimes, the group needs to hear someone repeat what they’ve done so far as well because someone may not have been following along. Hearing it repeated back can reveal the parts of it that don’t make sense.” (Erica Feedback)

Her suggestion is simply, “take some time to explain the methods of what you’ve all done so far”, but the feedback is far richer because Erica wrote several ways that this can be a helpful strategy in class. One of the hallmarks of Erica’s feedback was these lengthy justifications for her suggestions, which left no ambiguity around what Erica was trying to tell her students in the feedback and just as importantly why she was making the suggestion.

For all three LAs, justification of critiques was a core feature of their feedback. This feature of the LA-perceived feedback does not appear to originate from the course materials or training presentation. The LAs have chosen to adopt this feature because of their own experiences and values. The fact that they value justification so much suggests that the LAs have altered the feedback structure from its original form. The fact that they have shifted practice like this suggests that LAs truly have central membership in the P-Cubed instructional community (not just the LA community), because they have made the step from learning to take up practices to dictating how those practices are carried out at the highest level.

When we emailed the LAs to circle back to this theme of developing feedback, Erica provided an explanation for how she evaluates her own feedback-writing practice.

> "There is never a perfect way to have written feedback for a student. Knowing that helped me realize that as long as it's not daunting for the student to read and it conveys the message I want them to hear for the week, then I'll know I've written 'good' feedback by my standards." (Erica Email)

By evaluating her feedback against her own standards, Erica expressed a part of the agency that P-Cubed LAs have when carrying out their teaching practices. Though Erica was likely guided by course materials, training, personal experiences, and her fellow LAs, she emerged with her own criteria for her feedback. This is what P-Cubed was designed for, and it is why we claim that LAs in this context have had their own, real impact on feedback practices while still remaining grounded in the P-Cubed community and its traditions. The iterations that the LAs have made to the feedback mechanism can also be viewed from the perspective that the LAs are identifying crucial gaps in the curriculum design that need to be filled and are filling them. The need of providing justification with feedback seems abundantly apparent and yet it was never formalized in the training or documentation for the class. It is contributions like this to the curriculum design of the class that leads us into our next finding about SaP.

5.6.3 Learning Assistant influence through student-partnership

The third main finding of the paper is that the LAs in P-Cubed function as the student-end of a student-partnership. To be clear, LAs *are not* students in P-Cubed, but they *are* undergraduate students. They participate in the partnership by influencing the P-Cubed course alongside the corresponding faculty instructor. Because student-partnerships are defined largely along the relationship between students and a faculty member or university official, we foreground our interview with Roland in this subsection, where he discussed his perspective on his relationship with LAs when he taught P-Cubed and what he thought about the influence that LAs had. Since we saw in the previous subsection that the LAs have had significant influence on the practice of constructing feedback, we now explore how this partnership functions. We will show below that the breadth of LA influence extends beyond feedback and suggests that the LA community of practice (within the teaching staff community) in P-Cubed could be a model for employing LAs as partners in curriculum design. In order to demonstrate that a partnership centered around curriculum design is at work, we will show that LAs have a strong level of control over decision-making on curriculum and pedagogy in P-Cubed. This control is particularly important for a specific type of partnership: curriculum design and pedagogic consultancy, which requires significant participation and say-so from LAs [28].

From Roland's interview, it's clear he learned early on how useful LAs could be to a lead-instructor's decision-making. He reflected that he learned to rely heavily on LAs for running the course, in effect forging a partnership that gave LAs power as instructors that had major influence on feedback practice, teaching practice, and shaping the LA community. In his own words, "I think [LAs] bring a lot more to the class than any single instructor could possibly bring to the class, in all those different experiences" (Roland Interview). In talking of the different experiences, Roland was referring to the in-class experience LAs have as P-Cubed students in the past before they become LAs and also the experience of accumulating expertise over several semesters of teaching.

The partnership that Roland went on to describe applied more so to the veteran LAs than the newer ones. From his perspective, these seasoned LAs were often better suited to teach than even the graduate TA assigned to the course.

> "[The graduate TA] hasn't done that teaching in that type of an environment before. And if we get an undergrad LA, who has taught the class once before and was a student in the class once before, they tend to be better than first-time grad students doing the class." (Roland Interview)

In making this observation, Roland referenced the environmental preparation that LAs have, which makes them ideally suited to teach P-Cubed as instructors. We provide this quote to show

how Roland, as the faculty instructor, views the LAs—to him their teaching expertise is second-to-none. This quote also highlights that Roland also views the LAs as more experienced members of the teaching staff community than graduate students, even though graduate students may have more content knowledge in the subject and/or more years in the broader physics community. This sets up the partnership that Roland allowed to flourish by giving the LAs more responsibilities than would normally be expected from undergraduates.

The LA influence on teaching practice was most apparent when Roland described the role that senior LAs took up in his most recent semester of teaching P-Cubed.

> "I see the more senior LAs as being responsible for the day-to-day running of the class...they've done the class multiple times and they've seen a lot of the different issues and things you could run into." (Roland Interview)

Again we see Roland elaborating on the preparation these LAs have had by running into the same problems many times. He saw them as co-managers of the course and entrusted them with responsibilities that he would not be able to oversee, because he knew they were experienced enough to tackle issues on their own. This is one of the ways we are seeing the LAs have a level of control over pedagogy.

One of the day-to-day runnings that he entrusted to LAs was twice-a-week meetings to prepare for class. The meetings were held in separate groups to accommodate scheduling, and one set of meetings was led by a senior LA, whom we will call Fiona. Roland recalled how Fiona used probing questions, which he saw as reinforcements of good teaching strategies.

> "She did a nice job of breaking down the problems and making sure everything that we might conceivably run into in class was covered in these pre-class meetings, and asking and modeling good probing questions for the junior LAs...she did a really good job of modeling what good interactions with students would look like." (Roland Interview)

By Roland's account, these meetings were better for having been run by Fiona. Not only that, but she was able to model student-interactions, implying that she had an in-depth understanding of how students might approach the relevant problem. By letting an LA take up a position of power like this behind the scenes, Roland allowed for the LAs to take up central positions in the instructional staff as a whole. This had the dual effect of leveraging LA expertise to improve teaching practices across the whole staff and also encouraging a framing of P-Cubed instruction that centers LAs, which could be seen by old and new LAs alike. Even the LAs who did not have these bigger responsibilities could see that the partnership was at work.

The P-Cubed students also bore witness to this elevation of LAs because during class time, Roland's classroom was run by the same senior LAs that he talked about earlier in the interview. The way the room was set up put Roland on one side of the classroom. The other side he left to be managed by Fiona, the same LA who took charge of managing the class and helping other LAs when hard-to-manage situations arose during group work. He trusted Fiona to manage problems that arose among other instructors, and in his interview he commented on the peace of mind he had during class.

> "Sometimes what happens during class, [an LA] runs into something and they're unsure how to proceed with it. It was nice to have somebody who [LAs] could rely on on the opposite side of the room." (Roland Interview)

Through sharing management responsibilities at Roland's discretion, Roland and a handful of senior LAs forged a partnership where they all had their voices heard and their expertise appreciated in how the class was run. As described by Matthews [37], this quote from Roland exemplifies a "reciprocal partnership," where LAs' inputs are truly valued and not tokenized. This is an example in which P-Cubed teaching practices stand on the very top rung of the participation ladder in Figure 5.1.

The LAs themselves reflected in email correspondence that they felt their voices were heard on course decisions and how the class was taught. This signifies that these veteran LAs had central influence on the practices of the P-Cubed LA community, and it wasn't just Roland's perception. In Erica's email, she reflected on how she gained familiarity with P-Cubed's in-class problems over time, and eventually began making suggestions for improvements that would clear up sources of confusion.

> "Over time, I became more familiar with what each problem was made for: each problem had a concept it intended to convey through the story, and as that message became clearer to me, I became more vocal about places that were routinely confusing to me and in what places we could add more context or rephrase things to make them clearer." (Erica Email)

Erica only gave input on problem design after she felt that she had gained familiarity and expertise on what the problems were meant to be about in the first place. This highlights another benefit of having LAs participate in this partnership: their suggestions are grounded in the combined experience of dealing with the course materials from a student perspective (as former P-Cubed students) and an instructor perspective (as LAs).

The influence that LAs have in P-Cubed extends beyond the physics problems. In Carly's email correspondence, she discussed how she had an idea to change part of the structure for delivering feedback: rather than providing grades according to a written rubric, she wanted for instructors to input feedback into an app that mapped the rubric into a questionnaire that related more closely to experiences instructors would have in class.

> "I think that the professors and actual TAs had a lot of respect for the LAs and what they had to contribute...My ideas were taken seriously and either implemented or I was given clear feedback about why they weren't implemented. One thing that I contributed was a different method for giving weekly grades to students. Although it wasn't implemented long-term, it was trialed for a semester and it felt like I'd been able to move the class forward (even if it was more of a reassurance that the current method was still a good one)." (Carly Email)

Carly's app idea ended up on the back burner after a pilot semester, but it remains a testament to the power that senior LAs are granted in steering the teaching practices and feedback practices of

P-Cubed. A common concern of student-partnerships is that the input from less powerful members (LAs) is sometimes not taken seriously [29]. In Carly's case, her ideas were encouraged until they became full-on transformations of teaching practice and implemented broadly to test their efficacy.

Another, more direct example of an LA participating in decision-making around feedback structure was when Erica had a chance to give input to the EMP-Cubed curriculum, which is a P-Cubed-like course that covers introductory electricity and magnetism, first taught in Fall 2017.

> "EMP-Cubed was being developed and Paul [Irving] was sitting at a table, thinking about how to implement self-written feedback from students into the course structure. I sat and I brainstormed with him, and my idea of dividing the self-feedback so that it was slowly implemented in stages through the semester ended up being the structure that was implemented." (Erica Interview)

Though the context was not P-Cubed, Erica had forged a partnership with Irving in part from her role as an LA in P-Cubed. This relationship made it natural for her to provide input on a new course and reimagine what feedback practice could look like. In this way, the LA-faculty partnership had a tangible impact beyond the course where it began.

The last partnership-like impact that we will describe in this subsection is the roles LAs play when recruiting new LAs to the instructional staff. Roland described in his interview how LAs provide special insight during this process.

> "Like halfway through the semester, we'll discuss recruiting new LAs and solicit input from more senior LAs...the LAs might say, 'yeah, the person might ought to be this, but I'm not quite so sure about that.' So we get LAs who would say, 'I think this person would make a really good LA.' And having an LA approach one of the students in the class and say, 'you should really apply for this', I think that helps with recruitment." (Roland Interview)

He described their input as a solicitation, meaning he has sought out their opinions because he values what LAs have to say about potential applicants. The solicitation is another indication that there was a relationship between faculty and LAs through which Roland felt he could consult the LAs on the future of P-Cubed teaching. When he hears comments like “I’m not so sure” and “this person would make a good LA”, this helps him direct the way he thinks about the recruitment process, because he knows that many of his LAs know the current students much better than he does. He admitted earlier in the interview that he really only gets to interact regularly with 25-percent of the class over the course of the semester, which is why he relies heavily on LAs during the recruitment of enrolled students. This reliance points once again to the negotiation of LA control over the course. He also highlights the importance of having LAs encourage current students to apply, the implication being that P-Cubed students may trust the suggestion of an LA who went through that very same process.

We used Roland’s commentary on the helpfulness of senior LAs to show how they had a partnership with Roland wherein they were trusted to manage meetings and real-time in-class issues without the intervention of a faculty or graduate TA. This pointed to the responsibility that some P-Cubed LAs had, which rendered their class-wide influence akin to Roland’s. One product of this LA-based power was that they learned to work together to reinforce learning strategies for their students. As Roland recalled, LAs would identify broad needs in the classroom and work with their students via feedback and in-class teaching to help them improve along those lines.

> “Trying to reinforce [strategies], not just in feedback, but sitting down at the table with their students face-to-face and reinforcing in two ways. You’d have multiple LAs sort of reinforcing the same types of strategies...I think it just organically happened like that.” (Roland Interview)

Because of how LAs worked together and collectively had influence over a large number of students, they were able to impact in-class teaching and learning in a big way.

We also analyzed Erica’s journey with P-Cubed problem design: first learning to do the problems and gaining familiarity, and eventually providing feedback on sources of confusion and improving the LA solution guides. She seized similar opportunities to contribute to exam problems and homework, which she elaborated on via email.

> "I wrote exam problems fairly regularly since the beginning of my LA time, even up until now. It feels like having a voice, because my ideas are directly implemented in something a student receives and gets a grade on. Same thing for homework, like deciding my own help room hours or choosing how I can run those hours. It's like a real-time judgement call." (Erica Email)

She viewed these opportunities as "direct implementation" of her ideas onto the materials that students would go on to use. An area where she had total control was her "help room hours" where students would come to get help on homework, concepts, or studying. Erica was able to recognize the ways she could leverage her strengths and have the most impact as an LA. She put it very poignantly in her reflection, comparing this impact to a historical, indelible influence on the trajectory of P-Cubed.

> "It's sometimes scary, but it also feels very satisfying knowing that I'm putting a little bit of myself in the history of the class." (Erica Email)

Overall, we see many features of the course that demonstrate how these LAs have become central members of the instructional community alongside the faculty instructors and graduate TAs. Through the course design and the compliance of past instructors, LAs have been given responsibility for managing students, opportunities to run meetings and shape the LA community through recruitment, and in some cases seats at the table of curriculum development. And through these myriad opportunities, LAs have stepped up. They ran the meetings, they shaped and sustained the LA community through mentoring among their ranks, they took responsibility for carrying out teaching practices in accordance with their experience, they grew the LA community through recruitment, and they passed on these responsibilities to their protege LAs. The existence of the opportunities listed above and the strength with which the LAs have used these opportunities to wield control of the course are how we demonstrate the existence and characterization of a student-partnership among the P-Cubed LAs.

5.7 Discussion and Conclusion

The goals of this investigation were (1) to demonstrate the development of a community of practice among P-Cubed LAs, (2) to describe LAs' influence on the development of a specific practice (feedback) within that community, and (3) to demonstrate and characterize the partnership between P-Cubed faculty instructors and LAs. Though our first and second findings could be described as "outputs" of the partnership, we presented them separately to motivate the third finding and demonstrate how the partnership functions in a more detailed manner.

This study highlights two specific design principles that encouraged the development of an LA community of practice within the P-Cubed context: the feedback mechanism and the P-Cubed LA program. According to Irving et al [165], the feedback was designed to build trust between LAs and students, offer explicit suggestions for improvement to help students take up scientific practices, and legitimize student behavior when aligned with the goals of the class. The LA structure was designed into P-Cubed as a way of providing a social "bridge" into physics, because LAs can be seen both as experts and peers. In this way LAs were designed to be central members of the whole-class community. As we showed in our investigation, these design principles successfully set up a community of practice among LAs in a way that allowed P-Cubed students to follow a trajectory from physics-newcomer (just outside the periphery of the LA community) to veteran LA. Although this study does not explicitly investigate the student (pre-LA) part of the trajectory within the P-Cubed community of practice, the reflections on the journey from student to LA from our participants do highlight that their student experiences played important roles. This supports the notion that designing for the development of an LA community of practice can be a fruitful way to orient a classroom. For P-Cubed in particular, the LA program is a significant part of the manifestation of the CoP design.

For our context, an important part of the community-building process is that all the LA applicants are previous students from P-Cubed. Although it is somewhat typical for undergraduates to be recruited to be LAs for classes they have taken, our study indicates that this style of recruitment is essential for the P-Cubed LA program. It provides significant preparation for potential new LAs, who often join the staff ready to operate in the collaborative P-Cubed environment. Our LA interviewees often recalled how formative student experiences played into how they went on to teach. Roland, too, commented on how he believes LAs in P-Cubed are very well prepared for their role because of their familiarity with the material.

Another benefit of drawing from the P-Cubed students as an applicant pool is that existing LAs get to participate more authentically in recruitment. This feature in particular is a benefit to the LA community, because LAs get to have a voice in who becomes more central to their community. They do this by providing first-hand feedback on the character and preparedness of potential new LAs based on their interactions with the applicants as students. If applicants came from outside the class, the existing LAs would not have the personal relationships to draw from, and therefore would not get to participate in community management as closely. The CoP framework has an apprenticeship undertone to its set up, and LAs having a voice in the recruitment process allows them to choose the next set of apprentices that they want a hand in guiding. This allowance reinforces to the LAs that their voice matters with regard to the running of the class and maybe more importantly who becomes more central members of the community. However, input on recruitment has to be managed carefully as the culture of the community needs to place an emphasis on whether potential LAs are demonstrating aptitude in the practices and values of the class and not letting a creep towards a recruitment of LAs who are "similar" to them. For recruitment of new P-Cubed LAs, the existing LAs will encourage students to apply and recommend potential candidates that align with the community, as Roland described, but there is still an application form and an interview process supervised by the course coordinators before any formal offer is put forth. This ensures that an emphasis is placed on creating an inclusive community within the P-Cubed classroom and maintaining the goals (or, joint enterprise) of the community.

Despite the tight LA community that has flourished in P-Cubed, the CoP framework points to new ways it can be improved. In particular, we examine participation and reification. Though LAs have been able to change and direct what practices in the community looks like, their influence on the course has gone un-reified. A prime example of this is in our more detailed exploration on the practice of feedback in Section 5.6.2. The course materials around feedback still look the same as they did when the course was first offered, despite the many contributions that LAs have made to its structural components when they carry out the feedback practice and mentor other LAs in it. Since the practice has evolved, CoP would suggest that these changes should be reified in the course materials and shared repertoire of the LA community.

Furthermore, the process of onboarding new LAs through mentorship and expansion of the LA community is still almost completely undocumented in curricular design materials. This is potentially problematic because of the resulting instability around helpful strategies that LAs have introduced into the course. For example, a new program coordinator or a series of new faculty-instructors could completely change the enterprise of the feedback-writing practice, solely because of the current enterprise's heavy reliance on participation (without reification). The lack of opportunities for LAs to reify their transformation of the feedback-writing practice is problematic if the goal is to embrace LA-induced change. In order for this community to embrace the directions that LAs appear to be pushing the practice, there needs to be some mechanism in place for LA participation to be reified. Only through the duality of participation and reification can meaning be negotiated by all members in the community. Such a mechanism would strengthen the existing LA-faculty partnerships and allow the current LAs to contribute to the reifications of past curriculum designers. This would then better satisfy the structural change needed in good student-partnerships as outlined by Matthews [37]. In effect, LAs would be able to take part in negotiating and documenting an enterprise that represents the collective experiences and values of feedback-writers over time.

Currently, instead of integrating the adaptations formally, the class coordinators have instead let the practice of feedback transform organically. Organic transformation versus imposed reification opens up more possible research questions. For example, questions need to be asked about the formalization process—should practices be reified after they reach a level of uniform use by members of the LA community or is good practice just good practice and should be integrated immediately? One of the realities of curriculum design is that there is no one "right" way to teach. Maybe a level of uniformity being reached in how the LAs teach is an indicator of the utility of a change in teaching practice and a point at which reification should occur. At the very least, the feedback adaptations made by the LAs in this study and the lack of reification of those adaptations highlight the need to listen and pay attention to the teaching approaches of LAs as they might just have as much to teach us about teaching as we have to teach them.

One way to address the current issues around reification in P-Cubed would be to update the artifacts that exist in P-Cubed related to feedback, such as the assessment guide. By incorporating LA perspectives into course materials that would be used in future semesters, we can strengthen the positive influence that LAs have on the course structure. A more explicit strategy would be to administer exit interviews with final-semester LAs that could be incorporated into the materials as a way of preserving their legacy and the improvements that they made to the course during their time. A shadow of this idea exists in pre-class meetings, when notes are gathered on the confusing parts of the solution guide, which is then updated for future semesters. These strategies exist to a degree in P-Cubed, but they could be leveraged in other areas of the course and expanded to be a more explicit part of the curriculum development process.

Through our investigation, especially when examining how LAs have developed the feedback mechanism, we demonstrated that in P-Cubed there exists a partnership centered around curriculum design and pedagogic consultancy. In particular, this partnership is characterized by the long-term tenure of LAs and the lasting influence they have on teaching practices. The three tenets of a good student-partnership, according to Matthews [37], are at work: (1) Input from LAs is valued among curriculum designers and faculty, meaning the partnership is reciprocal. (2) All parties benefit from the partnership: LAs gain experience managing the community and bettering their teaching skills, faculty get classroom management help and get to learn from peer-learning experts, and P-Cubed students (though they are not members of the partnership) receive a more personal, relevant physics education. (3) The outcome of the partnership is broad and sustainable in how it has a lasting effect on the course pedagogy and the structure of the LA community among future generations of LAs.

Fulfilling these tenets is only possible because P-Cubed was structured for LAs to retain a direct influence on the course for years and the LA-end of the partnership comprises undergraduate student-instructors, as opposed to just students. The P-Cubed LAs have a special combination of expertise and opportunity, which allows them to influence the course structure in positive, lasting ways. Other curriculum-centered partnerships in publications are markedly different from the P-Cubed model. For example, Cook-Sather [168] detailed a model that utilizes one-on-one student-faculty relationships to reform curricula. Unlike P-Cubed LAs, the students in this model had not taken the course for which they advised. They instead learned about it by sitting in and gathering observations. LAs in P-Cubed are special because of their closeness to the course, having spent many semesters operating within the course. Also, the existence of a community of LAs helps them build expertise via collaboration, which from a CoP perspective makes their advising all the more valuable because it is more likely to be aligned with the values of the course and drawing from a broader selection of experiences.

In another example, Bovill et al [169] describe how students apply to course design teams for courses they have taken before. In their findings they noticed that the partnerships suffered because a lot of time elapsed before faculty in the teams noticeably ceded their authority and students began to feel like they were being taken seriously. In contrast, the P-Cubed LAs have a long tenure where they build trust with the faculty instructors (who often teach P-Cubed multiple semesters) and with the LA program coordinator (Irving). Their voices are heard semester-after-semester, and taken seriously, as shown in Section 5.6.3. The features that make the P-Cubed partnership unique are (1) the LAs' intimate experiential knowledge of the course, (2) the community of practice that exists among LAs and influences the course as a collective, and (3) the tiered nature of the LA community, which allows for more senior LAs to take up significant course responsibilities and make their voice heard on structural decisions without imposing the same pressure on more junior LAs.

In most partnerships, students are recruited directly into partnership whereas in P-Cubed it seems as though LAs gain credibility over time and are gradually consulted more and more on course decisions and given more and more management responsibilities the longer they are an LA with the class. Experience equating to credibility is one perspective, but an alternative framing could be that new LAs do not feel equipped or have enough expertise to wield their voice related to group decisions and instead defer to more senior LAs. The intertwined nature of experience and credibility needs to be investigated further in order to understand how a student-partnership borne out of an LA community of practice promotes and restricts the input of the LAs when it comes to curriculum input.

The path towards centrality through experience could represent a more natural progression to include student voices in curriculum development. The way P-Cubed is set up, LAs gain many experiences with teaching the materials and operating within the LA community before being offered some of the opportunities and responsibilities associated with the LA-faculty partnership (more accurately associated with the slightly larger teaching staff community) that we described. On the other hand, a potential problem with this model is that it privileges voices from more experienced LAs. There is the potential for a form of institutionalization to occur as LAs spend more time teaching the class with the possibilities of their inputs becoming more teacher-centered as opposed to student-centered. At what point do the LAs stop being students and instead take on more teacher-like perspectives, therefore losing the special influence of student-partners in curriculum design? They will never be responsible for the running of the entire course, but an open question becomes that for this SaP model, when do students become empowered enough that the source of their influence is no longer authentic student experience? This also makes us wonder, what would it look like for new LAs to infuse their voices into the course? We suspect because newer LAs are not as central to the culture of P-Cubed, the course would change faster but perhaps with less overall direction. The inputs of the newbie versus central member present an interesting future direction for SaP research, and we are interested to see research from course contexts that have utilized this more progressive approach to student-partnerships.

Overall, this investigation serves as a model for the fidelity of LA-driven student-partnership leading to structural changes in a course. The lesson here is that student-partnership for LAs is possible and can work well in the case of a course like P-Cubed that has been designed around CoP. As we discussed, the features that make the P-Cubed partnership particularly effective are the features that come from the LA community of practice that was designed into the course. By learning to teach via the community of practice, LAs gain intimate knowledge of what works and what doesn't when teaching, they wield collective expertise when collaborating with their peers, and they follow a natural progression towards a place where they have significant influence over the direction of the course. The way this partnership is rooted in the LA community of practice is what makes it as effective as it is. Re-conceiving LA programs as student-partnerships opens a path to incorporate LAs into and reinforce sustainable curriculum change.

5.8 Acknowledgments

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CHAPTER 6

STUDENTS' PERSPECTIVES ON COMPUTATIONAL CHALLENGES IN PHYSICS CLASS

This chapter builds on some of the research tools that I honed in Chapter 4 and 5: attention to context, qualitative case study, and connecting students' perspectives to theoretical frameworks. What makes this chapter special is that it takes place in the context of a computation-integrated high school physics class, a context that needs student-centered research and whose curriculum is developing rapidly. Due to the gap in research on students' perspectives in computation-integrated physics, this chapter focuses primarily on analyzing and cataloguing what students say, and secondarily on applying theoretical lenses to the data. This chapter has been submitted (fingers crossed) to Physical Review Physics Education Research for publication.

6.1 Abstract

High school science classrooms across the United States are answering calls to make computation a part of science learning. The problem is that there is little known about the barriers to learning that computation may bring to a science classroom or about how to help students overcome these challenges. This case study explores these challenges from the perspectives of students in a high school physics classroom with a newly revamped, computation-integrated curriculum. Focusing mainly on interviews to center the perspectives of students, we found that computation is a double-edged sword: It can make science learning more authentic for students who are familiar with it, but it can also generate frustration and an aversion towards physics for students who are not.

6.2 Introduction and Background

There are increasing and wide-spread pushes to introduce computation to high school students [24, 25, 26]. Integrating computational practices with STEM classrooms gives learners a more realistic view of what it means to do science, and better prepares students for pursuing careers in a world where computation is ubiquitous [40]. These pushes are also associated with changing standards [170] to teach our high school students how to “think computationally” [171]. As the push for integrating computation into classrooms becomes more prevalent, we must reckon with the problem that little is known about how students will take to computationally integrated science. This research study contributes to the effort to find out more about the student perspective towards computation when it is integrated into the science classroom. Here, we focus on a case of students experiencing computational integration in their high school physics class. By detailing what challenges and perspectives students face in this context, we can start to identify how to make computation-integrated K-12 physics more equitable, enjoyable, and beneficial to learning.

For our purposes, we view computational integration as the act of altering the curriculum of a STEM course to incorporate computational modeling, specifically as a tool to learn the STEM subject. In this way, students don’t learn to program separately from learning science, but rather they learn science in a new way, through computational modeling. This is a practice that STEM professionals are intimately familiar with [33]; thus, integrating computation makes STEM classes more authentic to future STEM careers. Authenticity is important in the sense that computation provides a way for disciplinary science practices to be featured and learned in the classroom [172, 173].

Computational modeling can be integrated in a variety of ways at the K-12 level. For instance, at the high school level, teachers have created models for planetary motion in an attempt to help students make predictions and discover Newton’s law of gravitation through experimentation on the model [33]. This approach involved the teacher creating the computational model and the students interacting with it. This integration focused on the practice of using computational models to explore physical phenomena. Separately, a middle school chose to integrate computation into science classes for fourth, fifth, and sixth graders [64]. The students used Scratch programming [174] to create simple models of situations of their choice. For example, one student modeled a projectile launched from a seesaw and got real-time feedback from the computer as they constructed the model.

Because Scratch uses code-blocks rather than text, it was easier for students to interpret errors and connect their computational choices to the model they made. Another example of computational integration, at the college level, involved curricular transformation in an introductory undergraduate lab-based course [65]. The labs in this course were redesigned to include one part traditional lab with hands-on equipment, and one part computational modeling with VPython [175]. The integration also included reflection questions to help students make connections between the programming and the open-ended, hands-on experimentation. One benefit to the students was that by learning the fundamentals of VPython, they were able to better visualize the relevant physics concepts in the lab course [65].

Despite the increasingly widespread adoption, what we know about how students learn in computationally integrated settings lags behind the speed of the changing curricula. As stated in a recent report on the state of interdisciplinary computation-integration-based education, "We still know very little about students' thinking and learning as it unfolds with the use of computational tools. At the very least, new tools for thinking and making sense of data call for curriculum resources that consider students' developing computational literacy. With the introduction of this new competency, novel effects may emerge concerning student engagement, motivation, and identity in computationally enhanced classrooms" (page 9) [33]. Essentially, Caballero et al call for researchers to develop an understanding of how computation impacts the experiences of students, from the perspectives of students.

To date, there has been no in-depth qualitative research on the affective experiences of students in computation-integrated STEM contexts in which to situate our study. We therefore looked to similar work in other contexts. To start, studies on affect and investigations of students' perspectives have been a major focus in the last 30 years in broader STEM education research [77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 14, 88, 89, 90, 91, 92, 93, 94, 95]. In particular, previous research in math has examined the affective impact on students when they engage in specific types of activities such as problem solving [77, 78, 79, 80]. An example of this is a case study on affective responses during problem-solving in a middle school math context [80]. Hannula demonstrated discipline-specific connections between affect and student success, thereby suggesting that attending to student affect in pedagogy offers a way to improve teaching and learning. In the discipline of chemistry education, multiple studies have been carried out that examine student affect or constructs related to it, like self-efficacy [81, 82, 83, 84]. In one study on student affect in an undergraduate chemistry lab [84], the authors observed lab classes and asked students about their affective experiences. Galloway et al's [84] findings and implications centered around students having complex, multifaceted affective responses. The authors offered several suggestions for teachers to cultivate positive affect and imbue meaning into the oft-rote manner of chemistry lab teaching. This study is important in that it was the first to study affective experiences in chemistry labs with an in-depth, qualitative approach, and the implications had the potential to make a significant impact on student-centered chemistry lab teaching. In particular, the authors drew from Bretz [85] to demonstrate that affect-focused research can provide insight into what students view as "meaningful learning"—an enterprise that combines learning with relevance and represents part of students' motivation to maintain effort in school settings.

Similarly, in physics education, research abounds on students' affective experience, beliefs, and perspectives [86, 87, 14, 88, 89, 90, 71]. One study points specifically to a gap we are trying in part to address—Gupta et al [86] argued that there has been a lack of research in physics education on the role of affect in modeling student learning, especially on fine-grain interactions. They made the case that most research on student-centered physics learning focuses on the content they know rather than their feelings about what they are experiencing [86]. To explore what role affect can play in learning, Alsop and Watts [87] looked at how students approached a physics topic (radiation and radioactivity) according to their attitude and perception towards it. Their study found that it was possible to balance "impassioned knowledge and informed feeling" in the learning of physics, which keeps students engaged but not off track. Some affect-based strategies for how to achieve this balance of engagement and learning were explored by Häussler and Hoffman [14] and Erinosho [88], who showed the importance (according to student perspectives) of linking physics with non-traditional and/or out-of-classroom situations [14], providing materials that had concrete, relevant examples [14, 88], and working on physics problems where students could collaborate with peers [88]. This set of affect-based, student-centered physics education studies demonstrates the relevance of affect to the field of physics education research, the need for deeper affect-based work [86], and relevance of affect for exploring student perspectives.

Additionally, there have been a number of studies that center on students' experiences in their computer science classes. Gomes and Mendes [176] suggested that students struggle in computer science because the necessary problem-solving strategies are new to students, especially in lower-level undergraduate courses, where a lot of students have their first exposure to computation. On top of that, students in these introductory courses are often experiencing the psychological stress of their first year in college in tandem with developing new ways of problem solving and thinking. From a broader perspective on computation, a study by Jenkins [177] highlighted specific barriers associated with the computational tasks themselves. He described computational difficulties in terms of a set of skills: coding (syntax, semantics, structure, and style), algorithms, and recipes for translating ideas into code. He argued that the hardest part is the novelty of computation; compared to other subjects, students need much more precision to achieve meaningful progress. This requires mastery over coding skills and some degree of expertise with translating ideas into code, both of which are hard to build when it is so easy to write imperfect code, to which the computer provides convoluted feedback or outright rejects.

Much of the research on students' experiences with computation, like the studies from Gomes and Mendes and Jenkins, focuses on the challenges that students face rather than their reactions to and perspectives on those challenges. Bosse and Gerosa [91] built a compilation of research studies centered around learning difficulties in programming settings. Most of the results from their literature review indicated students tend to be worried about learning syntax, variables, error messages, and code comprehension. Students also generally experienced nervousness with unknown coding concepts like functions and parameters, often resulting in students erecting affective barriers against such challenges. For example, when a student realized their code contained a semantic error, they were more likely to give up and not finish the programming activity because semantic errors take a lot of time and effort to identify and fix [91].

In the last decade, computational education research has begun to explore the relationship between affect and the challenges that students face in computer science courses. A relevant literature review focused on qualitative research in computation education [178]. They identified self-efficacy as a useful construct to examine students' experiences in these contexts. However, much of the existing qualitative literature on students' affective responses exists in advanced, undergraduate course contexts rather than more introductory levels. Additionally, they noticed that much of the qualitative work was trying to develop theories about how learning happens in computational settings rather than explore and explain computational difficulties from the perspectives of students. According to this review, there is a need in computation education to research on how students interpret their learning, especially at the introductory and/or K-12 levels [178].

A handful of studies address similar needs, though they are in short supply. Lishinski et al [92] studied students' affective responses to computational challenges and how difficulties can elicit negative self-efficacy judgments resulting in maladaptive learning strategies. They emphasize the importance of attending to affect in programming environments, writing, "Emotional reactions contribute to a feedback loop process in learning to program, and previous performance impacts future performance both by virtue of the effect that past experiences have on learning, but also via the effect that past experiences have on emotions" (page 8) [92]. A study from Kinnunen and Simon [93] similarly found that students made assessments of their own self-efficacy throughout the duration of computational tasks. Further, they found that affective experiences were the primary feature of computational work that students remembered after class was over. This brought an urgency to studying affect-based challenges in programming contexts.

The following year, Kinnunen and Simon [94] studied in more detail how students' affective responses were tied to their self-efficacy judgments. They found that self-efficacy was determined early in the course when students had their initial failures or successes with computation. They recommended that instructors should deliberately ensure that initial experiences with computation should include several successes because it is so easy to "fail" by writing imperfect code if you don't know how to interpret feedback from the computer, which is often inadvertently masked by confusing error messages. The same authors further studied the disconnect between affective responses and self-efficacy with longitudinal interviews [95]. In their findings they attributed the disconnect to a lack of reflective activities built into the course. They added to their previous recommendations by suggesting that initial computational experiences should incorporate feedback on the entire experience, not just the correctness of the result.

Studies like those from Kinnunen and Simon [93, 94, 95] and the recommendations that sprang from them demonstrate the importance of exploring student affect in a given type of learning environment. Eckerdal et al [179] theorized about why computer science learning elicits in students the affective responses that it does. They framed the initial experiences (where students form their self-efficacy beliefs for the first time [94, 95]) as comprising a "liminal space." In everyday terms, they asked, how do computer science students cross the threshold to learning? If it takes some persistence and confusion before students find their bearings in a computer science course, what is helping them get over the hump? The authors examined affect and found that as students crossed over the threshold, their feelings about learning computation transformed from hate and fear to euphoria. This implies that teachers can take clues from affect about where students are in the learning process, and even tailor instruction to help them cross the threshold to learning.

While there has been significant research into student affect and experiences in STEM courses, including computer science, this research has traditionally been siloed into separate disciplines. As computation becomes integrated into STEM courses, it is important to understand the effects of this integration. Recently, there has been some work that addresses the challenges associated with computation-integrated STEM, though not from a student-centered perspective. For example, one study investigated the ways that computational activities could be difficult in a middle school context [180]. The authors justified doing this in a computation-integrated STEM setting, writing, "learning a domain-general programming language and then using it for domain-specific scientific modeling involves a significant pedagogical challenge." They found that certain features, such as the problem-solving process and the syntactic complexity of programming languages, can be leveraged for learning by eliciting reflection on work or alleviated by employing a simpler programming language like Python. Overall, they relied on identifying challenges through observation of computational activities rather than through the perspectives or affective responses of students. The same was true in a study by Vieira et al [181], where the authors evaluated a computation-integrated materials science and engineering course. They found that it can be helpful to integrate computation with student-facing challenges in mind. For example, early in the curriculum students performed poorly on framing and recognizing computational problems, which could be addressed by providing extra scaffolding for problem-solving at the start of the course. This study, like Basu et al [180], based their investigation on performance metrics and features of the computational activities that could be construed as difficult rather than centering student perspectives or affect.

Several more studies in computation-integrated physics took up non-student-centered approaches but did allude to students' experiences at some point in their research processes. Weber and Wilhelm [182] reviewed broadly the history of computational modeling in physics education, and they identified several implementation-based hurdles, such as having students invest significant time to familiarize themselves with the software. This is especially a hurdle in high school settings, where there may not be time to learn a new programming language within an existing curriculum and learning to program could be harder at that level. Leary et al [72] focused on implementation-based challenges from the perspectives of university faculty. They found several faculty-perceived challenges: students being resistant to learning a new clunky tool, instructors not being able to devote enough time for students to get used to a programming language, instructors not having support from the department, instructors not being able to cover as much content, and instructors not having time to prepare for the new material. The authors relayed from their participants that it was hard as an instructor to prepare for computation because you must learn a lot about the programming language, and it can be hard to make sure it will be accessible to students who have not used it before.

Other studies highlighted the challenges *and* benefits to students of integrating computation into a physics setting. Svensson et al [183] viewed computation as a type of social semiotic, meaning it can be used to describe many different phenomena and it can produce many different answers to many different questions. In their view, becoming skilled at computation is like learning to communicate with a new language. An example of this is when students comprehend how a line of code that updates position is connected to the physical relationship between velocity and position. The authors argued the challenge lay in students having limited use of the social semiotic; even if you are aware of the affordances, you may not be able to use the semiotic resources skillfully. On the other hand, with proper guidance or computational experience, students can explore questions and create semiotic resources with code, and those resources can launch further inquiries. In the authors' view, we need to equip students to see the "affordances" of computational integration. We see a worrying alternative, which is that without an understanding of computation's benefit, students could adopt the view that they have an inability to learn languages (like having a "fixed" mindset [2]), and this could prevent them engaging with computation.

There are additional studies that highlight the student-perceived benefits that computation can bring to STEM classrooms. In an investigation on the impact of a Python-based, university-level computational integration [184], the authors reported that students were excited about learning computation, though the integration didn't have a significant benefit to learning until the second year of physics, when students who had learned the computational tools were able to leverage their proficiency with certain lab tools and data analysis techniques. Caballero et al [68] highlighted several other benefits that computation brings to physics. They focused their work on high school settings where Modeling Instruction [157] was in use, and they argued that computation highlights relationships between physics concepts, creates dynamic visual models, and can be used to explore real-world, complex physics problems because of its computing power. Furthermore, they explained that students who use computation are learning to use the tools that professional scientists use, which makes physics learning more authentic.

Furthermore, Caballero [70] interviewed professional physicists and physics graduates about how they use computation in everyday work, in an effort to paint a picture of what students should be taught in a computation-integrated physics course. The relevant skills (based on the interviews) were conceptual understanding of physics, writing pseudocode, computational thinking, connecting ideas between math, physics, and computation, understanding the purpose of using computation beyond analytic problems, and learning professional programming practices like writing comments in your code. The interviewees in this study were self-taught programmers, which further shows there is a need for these types of skills to be introduced into physics curricula.

Caballero et al [33] summarized the research on computationally integrated STEM classes and provided several recommendations for future research and implementations. They argued for the need to (1) develop approachable computational models that reflect modern science so that students can do science using the computation tools, (2) *study how computation changes student attitudes* and problem-solving, (3) promote proven learning standards when implementing computational integration, and (4) support teachers as developers of their own content and members of a computation-integrating community.

Thus, we see that research into computationally integrated STEM classes has begun to address the challenges of integration and the impacts on students; however, to our knowledge, there has not been a study that focuses on students' perceptions of the integration and the impacts on their affect, despite its importance in other areas of STEM and multiple calls for research. We intend for this study to begin to fill this gap and to focus specifically on the students' perceptions, challenges, and experiences in a computationally integrated physics course. With this setup in mind, we orient our research question: **What student-perceived, affect-based challenges do high schoolers face in computation-integrated physics?**

In Section 6.3, we describe the methodology that drives our use of the analytic tool and our choice around research design which is followed by a description of the study context in Section 6.4, including the teacher's choices around computational integration. In Section 6.5 we describe our methods for generating data, creating transcripts, and doing analysis. In Section 6.6 we outline and describe our results, specifically around student-perceived challenges, and we connect our results to affective literature in Section 6.7. In Section 6.8 we outline some of the student-perceived benefits of computation, and in Section 6.9, we discuss our findings and implications of our research.

6.3 Methodology

Our focus on student perspectives motivates us to use an interpretivist case study lens in this research. We describe this work as a case study because of our variation in data sources and because we aim to capture computational experiences of students in their natural classroom setting. In particular, we take an interpretivist lens because of our focus on students and their perspectives. The interpretivist approach [50] lends itself well to studies that focus on how people experience and interpret a phenomenon, as opposed to the phenomenon itself. Since we are aiming to open up an exploration of *how* students experience computation in their physics class, an interpretivist case study is ideal for exploring this in an in-depth, qualitative way. Using interpretivist case study, we would describe the crux of this study as "how students perceive and react to" affect-based challenges in computation-integrated high school physics with the case being a single physics class taught by Mr. Buford (pseudonym).

In determining our data sources, we bounded the "reality" of our case to the students themselves and classroom occurrences. For example, we did not study the home-life of any students to see how they dealt with their physics obligations outside the classroom. The reason for this bounding was to privilege data sources closest to the phenomenon: student interviews and classroom observations. Though students occasionally mentioned out-of-classroom experiences like school clubs or homework, we trusted the student's account of the experience rather than joining them for those experiences. Most of the discussion during class and during interviews revolved around in-class activities, which was the main way Mr. Buford had integrated computation into his physics class.

An important part of our methodology is to highlight the perspectives of students, who experience computation-integrated physics firsthand. It is their perspectives on that curriculum that this paper is about. We intend for our emphasis on participant interpretation to be coupled with a detailed discussion of the research context in which our participants operate. In the next section, we will outline the context of our study and introduce the teacher in whose classroom we generated our data. The rich contextual description we believe is important for practitioners to relate their own experience to and for researchers to understand the setting in which our case study played out.

6.4 Context

Mr. Buford teaches physics at Mulberry High School (pseudonym), a suburban, affluent, racially diverse public high school. He has been teaching at Mulberry for 30 years. In an interview with Mr. Buford, he commented that he tends to try to lean his teaching style towards problem-solving and exploration while still covering the material for the AP physics exams, which he estimates around half of his students elect to take the exam for college credit. He said, “I like to try new stuff,” and he confessed that he wishes he had more time to do wide-open, curiosity-driven activities in class: “I think I don’t do enough of, ‘Okay, so here’s this principle that you’re responsible for. Today we’re going to take some time, and you guys are going to brainstorm an experimental design.’ ”

One of the recent initiatives that Mr. Buford tried to introduce was computation. He was inspired in part by an existing computation-integrated introductory physics curriculum at Michigan State University (MSU) called Projects and Practices in Physics (P-Cubed) [63]. He began near the end of the 2017-18 academic year by going through the major physics concepts after the AP Exam. For each concept, he recalled, “I think about, does this one seem like it’s compatible with writing code to illustrate. Then I try to come up with a scenario, and this is just piggybacking on the scenarios that are used in P-Cubed.” For him, the computational activities were meant to be visual, and he used the GlowScript programming language [185] along with a minimally working program to do this. A minimally working program [186] is a piece of starter code that will compile without errors and create a visual; however, there are lines of code that need to be edited or added by students to create a realistic physical model. For example, Mr. Buford once introduced a program that showed particles passing through an optical lens without refracting. The task was for the students to break down their understanding of optics into steps so they could edit the computer program accordingly and get the particles to refract. Mr. Buford would generally begin the computational activities by explaining the minimally working program to the entire class. He would also explain what the output of the code should look like when completed by either running a solution code or drawing the output on the whiteboard. After Mr. Buford finished this explanation, he distributed the program and students were free to work together to create computational solutions.

During the summer of 2018, Mr. Buford attended a workshop at MSU entitled Integrating Computation in Science Across Michigan (ICSAM), funded by an NSF grant with the same name. The weeklong workshop was designed to support high school teachers who wish to integrate computation into their physics classrooms. During the workshop Mr. Buford collaborated with other teachers and facilitators on learning to do physics with GlowScript, and by the end of the week, he made a personalized plan for integrating computation into his curriculum for the upcoming year. While Mr. Buford had begun integrating computation at the end of the previous year, he began using it on a regular monthly basis in his AP Physics 1 and AP Physics 2 classes in Fall 2018.

Mr. Buford described in his interview how the computational activities would unfold in class.

MR. BUFORD Grab a laptop and fire it up, and then I go through maybe five minutes—I try to keep it as short as possible—a little explanation of what we're doing, and tell [the students] where to get the starter code and put it in GlowScript and start working.

Generally, Mr. Buford would project the minimally working program, or starter code, which he wrote himself, up onto the whiteboard, so students could see as he read through the program's code. Then he explained how important bits of the program worked, ran the program to show the visual at its minimally working stage, and described how it would need to change, occasionally drawing parts of his explanation with diagrams on the whiteboard. Sometimes, he will take a couple minutes near the end of class to project his solution on the whiteboard, so that he can explain a possible solution path. Even though Mr. Buford was showing his own solution on the whiteboard, he would always emphasize that many different solutions exist to the coding projects.

When designing the computational activities, Mr. Buford's approach was to build in checkpoints that students can reach, even if their solutions depart from what he might have in mind. "The ideal to strive for is, 'Okay, now that you've done that, now do this,' and actually have several of those in the bullpen waiting." When he says this, he is talking about progress students can *see* in the GlowScript animation window. In the optics activity for example, students can reach these checkpoints first by causing a light particle to move on screen, and then pass through the lens, and then refract, and then add more particles to the animation. Mr. Buford's aim is for students to progress along these steps so no matter how far they go, they still have some sense of success. His main difficulty with this approach has been, "students who struggle can still be working on that initial problem." Some students are not even getting past that first step, so they don't get to experience the scaffolded nature of the activity, or even a little bit of tangible progress.

The process by which Mr. Buford designs these activities is to first write the solution himself, and then take out the bits and pieces that he thinks the students should be able to rewrite.

MR. BUFORD I'll try to think of a scenario that's amusing, at least to me, but still is doable. The physics is right in the ballpark of the physics they're supposed to understand. Then the part that I'm not very good at is how much code do I give them, because I give them some starter code...I'll write code that will do what I want it to do, and then I have to try to pick the parts that I would take out and change... and then have them try to figure out how to make it work.

Thus, Mr. Buford tries to address multiple concerns when writing these activities. He tries to balance how much starter code to give students and how much to leave for the students to do, while at the same time making sure that the difficulty and physics content of the problems are appropriate.

Mr. Buford also made some design choices around *when* the computational activities feature in the curriculum.

MR. BUFORD Those coding activities are culminating activities to studying a concept...It's usually after we've talked about something for a few days or worked on something for a few days. We'll do a coding activity if it fits.

INTERVIEWER Is that intentional, to have it be after they've learned the concept in part?

MR. BUFORD Yeah...could you use it as a way of developing concepts? I think you probably could. I just haven't done that. I haven't used it that way.

The computational activities in Mr. Buford's class are designed to wrap up a unit. Students have already spent several days learning about a concept, and then Mr. Buford inserts a computational activity. He doesn't use the computation activities to introduce new ideas, rather they are used to reinforce what students have already learned and to apply those ideas in a new way.

When asked to expand on his views towards computation at the end of the unit, Mr. Buford talked about the importance of visual modeling and coding skills:

MR. BUFORD I hope it just enhances them thinking about the physics concept that we're trying to learn, ideally...I feel like when you're writing the code for this, you have to understand how projectile motion works, or you can't write code that models that very well...I guess my hope is that that's what we're doing is reinforcing the concepts, and at the same time I just think writing code is just a skill that's so valuable in lots of other areas besides just physics.

Mr. Buford wanted the computation to serve as a way to enhance and reinforce conceptual understanding of physics. His belief is that you won't be able to figure out the computational activity if you cannot figure out the underlying physics.

On a separate thread, Mr. Buford wanted the computation to serve as a way for his students to learn a skill that is widely applicable outside the realm of physics.

MR. BUFORD This computational modeling is so appealing to me. It's new. I'm not an expert programmer. I have students that are really good at it. It's cool to see what they come up with and how they come up with it. From my perspective, the problem-solving aspect of that I think is really valuable. The organization and the logic behind it, oh, my gosh. I think those skills are fantastic to have.

From Mr. Buford's perspective, these activities were about more than just physics; they were about building new skills and letting his students' creativity shine. Mr. Buford chose to not grade the activities:

MR. BUFORD It's okay to not have a grade assigned to every activity in your class, especially with students that are in advanced classes. You don't have to get something for every little bit of effort that you make, so it can be its own reward.

He believed that the opportunity to play with the program and create something intrinsically rewarding was enough motivation for his students.

The computational conditions that Mr. Buford created in his classroom set up the environment that his students were working in and informed the perspectives from students that follow in this study. We include Mr. Buford's perspective here to help readers understand some of the driving forces behind the development of this instance of computational integration. In the sections below, we focus our investigation on the perspectives of Mr. Buford's students, who are the only ones that can tell us how these newly integrated computational activities affect their feelings about themselves and their learning in this context.

6.5 Methods

We begin our methods section by introducing our student participants, who will be the main focus of our study. The students were selected to represent a broad range of prior experiences (in terms of physics classes and computational exposure) and in-class experience (determined through in-class observations). The aim was not to generalize our results to any sort of population. Rather, we chose a diversity of research participants because we wanted to describe the variety of challenges students faced in Mr. Buford's class. The class we focused on in this study was Mr. Buford's AP Physics 2 in the 2018-19 academic year. To ensure we respected how the students wished to be represented in this study [187, 188], we asked the students after data generation for their gender identity, racial identity, and preferred pseudonym.

Otto was a junior at Mulberry High School, and he took regular Physics 1 with a different teacher before enrolling in AP Physics 2 with Mr. Buford. He always felt behind and that this put him at a disadvantage when it came to the computational activities with GlowScript, because he didn't have any background with the language. While he did take AP Computer Science the year before, Otto often felt frustrated that his computational background didn't seem to help rather than feeling prepared for GlowScript. Despite his difficulties with GlowScript, he did well in the class, and tended to approach computational activities with the stance that he could just ask Mr. Buford as many questions as it took to figure it out. He usually worked together with Blaine, who also did not take AP Physics 1. Otto identified as a white man.

Circe was a junior at Mulberry and took AP Physics 1 with Mr. Buford the year before. She usually worked in a large group of six to eight other students who took AP Physics 1 together, including Beck and Ed, and felt a strong sense of community in the class. Often, Circe felt that the computational activities were too hard to authentically engage in, so she usually ended up copying someone else's code toward the end of the period and passing on a working program to someone else, calling it a "copy train." Other than AP Physics 1, Circe had no prior experience with programming, and she did not feel like she was "cut out" for programming or for physics. Despite this, she gave a poster presentation with a couple other students at the state capital about the cool things you can do in physics with GlowScript. Circe identified as a cisgender Central Asian woman.

Beck was a junior at Mulberry, and he took AP Physics 1 with Mr. Buford the year before. He worked in the same large group as Circe, which was usually formed at the start of class with students dragging three tables together. Beck was an avid coder, and he decided to learn more GlowScript and do Khan academy physics over the summer after taking AP Physics 1. His dad was a computer scientist. Beck felt that the computational activities helped him understand physics concepts better because it was like "explaining it to the computer." Because he could finish most or all a computational activity without help and he liked to share his code and explain his thinking to other students, Beck was often a resource for other students. Due to his relatively uniform positivity with the computational activities, he did not discuss challenges with much depth. He did, however, describe many positive aspects of computation. As a result, he does not feature in the next section on challenges but does in later sections of the paper. Beck identified as a white cisgender man.

Blaine was a junior at Mulberry, and he took regular Physics 1 together with Otto before enrolling in Mr. Buford's AP Physics 2. He took a helpless stance towards the computational activities, and he was never able to finish an activity during the class period. During one class, he threw his hands up and said, "what's the point of learning code? I can draw this on a piece of paper in fifteen seconds." He often sat with Otto when doing computational activities and he frequently expressed apathy towards programming. His only prior experience working with computer code was when he spent a summer in middle school with his uncle, who worked at a university. Blaine would try to work through programming tutorials while his uncle worked, but he felt like he didn't really understand any of it. Blaine identified as a cisgender biracial (Black and white) man.

Joyce was a junior at Mulberry, and she took AP Physics 1 with Mr. Buford the year before. She usually worked by herself but she also socialized with the larger table, especially after she was done working and ready to share her solution or answer questions. Joyce always finished the computational activity and was often the first in the class to do so. As a result, she spent a lot of time explaining her ideas to other students after she was done. Despite this role, she viewed herself as an average programmer, arguing that she couldn't solve the problems "in five minutes." She was enrolled in AP Computer Science at the same time and thought that the conceptual ideas from her computer science class helped her when she was using GlowScript. Joyce identified as a cisgender Asian woman.

Ed was a junior at Mulberry, and she took AP Physics 1 with Mr. Buford the year before. She had some additional prior programming experience from participating in robotics club competitions and writing instructions in code for the robots. Typically, she worked in the large group with Circe and Beck, and she tried to figure out and understand the computational activities, opting to ask for help from Mr. Buford or peers rather than join the "copy train" when she got stuck. She said in her interview that she was able to figure out the computational activities around one-third of the time,

Data Sources	
Student interviews	Six interviews and three follow-up interviews (follow ups with Otto, Circe, and Joyce)
Teacher interview	One interview
Field notes	Six class periods
Classroom recordings	Two group recordings during one class period, capturing all participants except Circe and Joyce

Table 6.1: Four types of data sources: student interviews, a teacher interview, field notes, and classroom recordings.

and this made her feel like she had the ability to successfully program every time. She also felt a strong sense of community in the class. Ed identified as a Black agender person. She clarified that she goes by she/they pronouns and suggested for us to pick one to use or alternate between she and they. We opted to use she/her pronouns alone for consistency.

6.5.1 Data Generation and Transcription

We developed interview protocols and conducted semi-structured interviews [45] with the above six students in Mr. Buford's AP Physics 2 class. The interview questions were aimed to elicit and discuss their feelings about physics class and computational activities in accordance with our research question. We also interviewed Mr. Buford for the context in the previous section, we took field notes during classroom observations, and we recorded two groups of students working on a computational activity during one class period. The data sources are summarized in Table 6.1 In this study we focused our analysis on the six student interviews, though we sometimes used in-class occurrences to shape interview questions and prompt responses to things that students did or said during the computational activities.

The interviews were transcribed for utterances. This choice was driven by a focus on what participants say about their experience, which aligns with our choice to use interpretivist case study. The interviews were conducted to ask about the perspectives of the research participants, and their comments are taken to represent those perspectives. We understand that interview comments can only *represent* how someone feels about their experiences [189], but still we foreground what the participants say, because their responses were prompted verbally. We included non-verbal communication in the interview transcripts when it added meaning on its own to what a student said, such as a head-slap or eyeroll.

6.5.2 Data Analysis

To analyze the interview transcripts, we identified episodes from each interview where the discussion centered around computation, physics, or feelings the student had towards the related classroom activities. It turned out that each interview yielded ten to fifteen episodes of one to two minutes each. The goal with chunking our data like this was to group utterances together into comprehensive statements from the students about their experiences with physics. We carried out analysis on these episodes by taking notes on the episodes one-by-one, and then tracing out patterns across the different episodes and interviews. We named each pattern according to the common experience or challenge that it represented for students. These names dictated our organization of the first findings section (Section 6.6). After outlining and describing the student-perceived challenges, we discuss how the challenges relate to affective constructs, such as mindset, self-efficacy, and self-concept.

6.6 Student-Perceived Challenges

We explore the question of *what student-perceived, affect-based challenges high schoolers face in computation-integrated physics* by presenting the interview data in which our high school student participants described their experiences and feelings around doing computation in their physics class. In the results below, we describe patterns in the data that constitute different affective challenges that students face when doing computation in Mr. Buford's class. The challenges listed below are in no way exhaustive, nor are they necessarily confined to computation-based settings, but instead represent an initial set of challenges experienced by students in this context. In the order presented, we address Stress/Frustration, Strain on Physics Knowledge, Unbelonging and Stereotypes, Responses to Setbacks, Interpreting Code, and Contextual Challenges.

6.6.1 Stress/Frustration

One of the main challenges posed was the additional stress that computational activities brought to students in Mr. Buford's class. Stress often accompanies new experiences but what made this a challenge was that students often saw the stress as uncalled for. They felt that they already knew the relevant physics concepts, and computation was just forcing them to jump through hoops in order to translate their physics knowledge into code. These experiences were often accompanied by frustration when difficulty was unexpected. The unexpected frustration and the unnecessary stress combined to make students feel unprepared and inclined to give up.

When Circe talked about stress in the interview, she spoke more generally about the stress she felt during all computational activities and coping strategies she employed.

> CIRCE I feel like it's just unnecessary stress, and I'm not about to put myself through that. So I just kind of sit there with the people, and we just talk and wait for one person to figure it out. Like I said, a copy train.

She felt stressed out during the computation, and her reaction was to not "put herself through that." Rather than confront the difficulty and "unnecessary stress" head-on, she opted to copy answers along with the rest of the group. Her response was to disengage, indicating either that she did not believe she had the ability to figure it out or that the stress of sticking it out was not worth it.

At another point in her interview, Circe talked about how the computational activities, or "code" as she put it, frustrated her. During this discussion the researcher (Hamerski) asked a question to get an explanation for what she meant.

INTERVIEWER What about the code frustrates you?

Circe It's like, you think that you should do a certain thing, input a certain value, or a new part of the thing, and you do that, and it's just completely wrong. And you sit there and you're like, 'okay, well, freak you, coding!

Circe felt like even when she made everything right in the computer program, or seemingly right, it ended up being completely wrong. There was no middle ground when it came to computation, and this made her feel that she couldn't do anything right during the activities. Her response was to sit there and feel anger ("freak you!") towards computation. There was no resolution, only frustration and giving up.

Another student, Ed, also discussed experiencing significant stress, but she did not disengage as readily as Circe did. Ed's stress was also "undue" as she said below, and it had to do with a tension between the computation and Ed's physics knowledge.

Ed I feel like [computation] causes me, sometimes, a lot of undue stress, which is like 'Oh, you don't know this and this and this.' So it's like, 'you do, you just think about it in a different way, but that's not a way that can be programmed on the platform.'

She felt stressed because of how the computation challenged her physics knowledge. The stress was associated with the feeling of not knowing, and she had to coach herself out of the difficult feeling essentially by saying, "you do know physics, it's the computation that's confusing." The "undue"-ness of the stress made it seem as if Ed viewed physics-through-computation as inauthentic physics, because she *does* get it when it's just physics.

Ed also felt some unpreparedness for the computational activities. When asked about whether she saw herself as "good at the coding activities," she responded by commenting on the frustrations of seeing the physics content being stripped of its familiarity.

Interviewer Do you think you're good at the coding activities?

Ed Not really, actually, which is kind of sad for me to be honest, because you have this interest in something, but it's back to why physics is so frustrating, because it's

> something that's like 'Oh, this is familiar, I know this,' but then it's just slightly slanted a little and just becomes, because you expect it to be this way so much, when it's this way, it's just, you can't handle it.

She linked her negative self-evaluation to a frustration about physics in general. She compared her computational frustration to the well-known experience of learning physics concepts that seem to defy intuition about how the everyday physical world works. Computation made familiar material confusing. Ed felt like she built expectations for how her ideas would play out in GlowScript, but it never seemed to work out—she couldn't "handle it." From this example, we see that Ed deals with her frustration by separating out the physics, which is familiar, and she understands, from the computation, which defies her expectations and causes her stress.

For Circe and Ed, computation added an extra, needless stress. Their reaction was to find ways to avoid the stress. For Circe, this meant copying others' solutions. For Ed, this meant separating physics and coding in her mind as a defense to preserve her self-view as a competent physics student. Other students also experienced stress but did not articulate it in these terms, such as Blaine becoming apathetic towards computation after repeatedly getting stuck or Otto feeling stumped and behind because of his lack of previous GlowScript experience. Both of these accounts are described further in the other challenges below. Students who experience stress may have a harder time building a resilient self-view of their computational competence, because it is easier to brush it off as, "I'm good at physics already, this is just me being bad at computation." It is much harder to swallow the pill labeled, "I'm not as good at physics as I thought."

6.6.2 Strain on Physics Knowledge

Another challenge students faced was the way that computation seemed to test the strength of their physics knowledge. This isn't necessarily a bad feature. After all, Mr. Buford wanted the computation to "enhance them thinking about the physics concept that we're trying to learn... I guess my hope is that that's what we're doing is reinforcing the concepts." For some students, the "enhancement" of physics thinking instead meant that they had to reconsider what they knew for the purposes of the computational activity, and this reconsideration often led to feelings of incompetence at either physics or computation. A prime example of this challenge is when Ed felt "undue stress" in the previous subsection. She recalled thinking, " 'Oh, you don't know this and this and this...You do, you just think about it in a different way, but that's not a way that can be programmed on the platform.' " She had to tell herself that she *did* know the relevant physics, but just not in a computation way. In effect, she separated the two domains (computation and physics) in her mind, so that her difficulty with computation wouldn't affect her view of her physics competence.

Later in her interview, Ed reflected on how she viewed the connection between computation and physics. She even suggested that computation changed her physics knowledge.

> ED I think coding definitely affects my perception of my own knowledge about physics... GlowScript especially, I feel like it caters to a very specific kind of learner, a very specific way of learning physics...it just requires you to take apart the numbers in a very strange way. Well, it's not a strange way, it's a strange way *for me*.

She felt that being good at computation (especially GlowScript-based computation) was like being good at learning physics in a special way. Ed felt unable to learn in this "strange way." When she struggled with computation, it felt like the class was redesigned with a different type of physics learning, and Ed's physics knowledge did not line up with the "very specific way of learning physics."

For Joyce, *getting stuck* during computational activities is what made her question her physics ability. Her self-doubts about her physics knowledge were rooted in not being able to translate the formulas she knew into code.

> JOYCE Sometimes it's made me think that I'm not as good at physics because when you do everything that seems right on there, or if you use that equation, you get

the right answer on your own, but you can't program it, then that made me feel challenging.

Joyce linked her GlowScript-based struggles to feeling bad at physics. This happened when she felt like she programmed everything right and she knew how to do the problem on paper, but it still didn't work on the computer.

The challenges that Joyce and Ed reference in the interview excerpts are not necessarily a bad thing—in fact it may be a sign of growth and learning that they are being forced to reconsider their physics knowledge in a way that aligns better with computational demands. However, these experiences are challenges all the same and must be addressed because they pose real concerns for students. For both Ed and Joyce, computation forced them to reconsider their physics competency because they felt incompetent when doing physics with computation. We do not have the data to say whether these feelings of incompetence were temporary, but it is clear that they constitute real affect-based challenges when doing computational activities.

6.6.3 Unbelonging and Stereotypes

The feeling of not belonging in computation and/or physics was also present in Mr. Buford's classroom. This challenge isn't necessarily brought on by the implementation of a new curriculum, but difficulty with the learning materials can exacerbate existing feelings of exclusion. Furthermore, computational physics is the intersection of two of the most exclusive STEM fields (with one exception: Black students earn a slightly higher percentage of computer science degrees than they do STEM degrees) [190]. As an example of a student feeling out place, we look to Circe, who talked at length about this when she thought about the computation in Mr. Buford's class. In the excerpt below, Circe noticed patterns among her peers related to computation and physics. She used the word "coding" to refer to the computational activities.

CIRCE I think I've noticed that there's people who are really good at physics that are also really good at coding. I think there's a pattern there. I have a lot of friends who are really good at coding, and they're usually really good at physics, and vice versa. It's like, I don't know. I guess it's all the same kind of brain.

Circe compared being good at physics to being good at computation. She had noticed that her friends were good at both, and there seemed to be a connection. It's "the same kind of brain," she said, which indicates that she viewed her peers' academic abilities as intrinsic qualities that they had. The language she used suggested that she saw herself on the outside of this peer-group: "I've noticed that there's people," "[my] friends," "they." By using otherizing language, she positioned herself as *not* having the same type of brain, indicating that she saw herself as not naturally cut out for physics and computation like some of her peers seemed to be.

Later in her interview, the conversation again turned to her sense of belonging in physics. Circe had established earlier that she wasn't interested in pursuing physics after high school, but she went on to imply that computation somewhat confirmed her thinking.

CIRCE I don't know if coding makes me feel like I don't belong in physics. It doesn't make me feel like I do belong in physics.

She was sure that computation was making her not want to be a part of the physics community. Even though computation may have been integrated into the course as a way of making physics more authentic to students, it had the effect for Circe of keeping her from building a sense of belonging.

In naming and characterizing the challenge of not feeling cut out, we acknowledge that many students choose to leave physics, and this choice can be in line with their interests and based on a realistic understanding of what it means to do physics and be a part of the physics community. However, many students can build views of physics or computation based on stereotypes of who does physics and unrealistic views of what physicists do [191]. One possibility, based on Circe's views about the "kind of brain" that is made for physics, is that she has bought into some of these stereotypes, particularly to be good at physics you must be an innate "physics genius" [192].

Similarly, we see stereotypes of programmers and programming show up in the classroom. We say "programming" here because often the students who adopt these stereotypes do not distinguish between the computational activities (where student program physics) and more general programming. An episode that encapsulates this view is when Joyce discussed why she felt like an average student despite her repeated success at the computational activities.

JOYCE I think I'm better than average, which is someone who doesn't know how to code at all. But I'm not... I can't just look at the scenario and just code it in five minutes. I'm definitely not that kind of person. I don't know. Just average I guess.

Joyce believed she was average compared to all programmers, implying that people who can look at the problem and do it in "five minutes" are the good programmers. None of her physics classmates would land in this category of speed, but she compared herself against this imagined programming genius anyways. This led Joyce to feel average despite being one of the most competent programmers in her class.

Stereotypes like the genius, five-minute coder can make computation feel inaccessible, and it can make it hard for students to build a sense of belonging in computation and/or programming. The challenge of stereotypes lies in this perception of unbelonging. The fact that some students must overcome this perception *and* still perform well in class in order to see themselves as computationally competent is a significant barrier.

The integration of computation into physics leaves the physics classroom open to stereotypes about programming *and* computer science. Students have understandings of what it means to contribute to computer code, and sometimes those understandings are built on unrealistic stereotypes about who does programming, what programming looks like, and how people become programmers. This is on top of the stereotypes of what it means to do physics, who gets to do physics, and how one can succeed at physics (e.g. "physics genius"). The prospect of computation introducing even more stereotypes into the physics classroom poses a significant challenge.

6.6.4 Responses to Setbacks

Due to the open-ended nature of the computational problems in Mr. Buford's class, many students had difficulty working on them. For example, there were many places where students were confused, encountered errors, or did not know how to proceed. How students reacted in these moments could lead them to interpret their experiences as failures or could lead them to success with the problem. For students that do experience success, it can have a positive impact on their affect. For students that don't, it can be devastating.

From Otto's experience, he often found success with the computational activities by working through his difficulties and trying to simplify the problem. Even though the activity was confusing to him, he felt like he could make sense out of it after thinking about it. He walked us through his general approach to computation in Mr. Buford's class.

> OTTO When I'm working through it, I'll be like, 'this is confusing.' And I'll start working through it. I'll try to simplify it to something that I can understand. Then I'll usually be able to think about it and be like, 'Yeah, that makes sense. I can implement that.'

Otto's strategy to deal with confusion was to simplify the problem until he understood what he needed to do. When he said he was "usually" able to figure it out, he indicated that there was a pattern in his approach to computational activities. The phrase he told himself was, "I can implement that." Whether or not he succeeded, Otto usually came to a point during computational activities when he at least *felt* like he could, even if he started the problem feeling confused. As a specific example, he remembered getting stuck and eventually figuring out a complex computational activity about the motion of charged particles in a magnetic field.

> OTTO There's a part where you had to use vector cross products to show the direction in which it would be moving, from like the direction of...the field and its movement already. That clicked a little bit after I realized how that function worked.

Though he encountered a confusing function, he figured it out. The function in question was the cross product function. His success in getting the function to work and understanding it is evidence of Otto's persistence in face of his typical computation-based confusion.

For Ed, experiences of success were more rare but not unheard of. When she did finish a computational problem it made her feel like she could do ANY of them.

> ED On like one out of the three times we coded, each of those one times where I've actually finished the whole thing, that always makes me feel like, 'well you finished that one, you can probably do all of these.'

Approximately one out of three times, Ed could figure out the code, and it was a big confidence boost. For her, it was the act of completing the program that made her feel the sense of attainment. Though she usually didn't finish, on the times that she did, it was a reaffirmation that she had the ability to succeed at doing the computational activities. The intermittent successes sustained her.

Blaine, on the other hand, discussed how he had recently given up on engaging with computational activities because of his inability to achieve anything that resembled progress.

> BLAINE I mean, I would try if I could literally get like anything. But since I literally can't get anything but a blank screen, I don't really try to do any more cause I'll put in a hundred things and then I'll just get a blank screen or I'll get some error.

No matter what he tried, Blaine always got the same result: "a blank screen or some error." Both results are associated with a non-working animation, a fate to which Blaine had resigned himself. Not only was this a wholly negative self-evaluation, but it was also a source of apathy and disengagement for Blaine. He experienced repeated and unrelenting failure. He came to associate computation with incompetence.

> BLAINE I just, I just don't even care. I'm like 'whatever dude. I can't do this shit.'

He felt like he couldn't do the activities to the point that he just didn't even care anymore. He provided a sharply negative statement, saying, "I can't do this shit." He had no successes with computation, and by the point of the interview he had given up entirely. Blaine was one of the two students who did not take AP Physics 1, so his first exposure to computation-in-physics was Mr. Buford's class. This points to the importance of having positive experiences and moments of success when learning a new curriculum as suggested by Kinnunen and Simon [94]. Blaine has no memories of success and therefore no hope that he will improve.

All these students experienced setbacks or confusion in the computational activities. While Otto would persist through those moments and eventually figure it out, the rarity of success at computation buried Blaine in feelings of apathy and inability. Ed had enough positive experiences to feel competent, but all the same it is concerning that some of Mr. Buford's students are not having positive experiences with computation. The prospect of students developing negative views about computation after repeatedly failing at computational tasks presents a unique challenge, especially when these failures are tied up with their first impression of computation-in-physics.

6.6.5 Interpreting Code

Another common challenge was brought on by the need to interpret code and errors in GlowScript. Often students felt that they had a decent understanding of how to use the relevant physics and apply it to the context in which Mr. Buford set up the computational activity. The challenge came when they received an error message or had to interpret or write code to execute their ideas. The elusive meaning of the error message or the challenge of using GlowScript syntax was enough to derail the activity for these students.

For Blaine, the computational activity that he described involved modeling rays of light passing through an optical lens. He had trouble with the very first step because he couldn't figure out how to use GlowScript to animate a line to represent the light ray.

BLAINE I feel like I'd like [the coding activities] if I knew what I was doing. I literally wrote ((laughter)). I literally wrote 'line', just like 'line period', to try and get a straight line. I don't know anything!

When he talked about what it was like to troubleshoot after getting stuck, he laughed about how little he understood GlowScript. He *guessed* at what the proper syntax would be because he had no basis for how to create something that looked like a line. He attributed the whole experience to his lack of knowledge: "I don't know anything!" This admission was reaffirmed when Blaine described his inability to interpret an error message because it referred to "line 17", or the seventeenth line of the computer program, which he was unable to interpret.

BLAINE I'll get some error. 'Line 17.' Well I don't know! I don't know what line 17 is, man.

In this case, Blaine couldn't interpret the error message that the computer provided. His responses about "not knowing what line 17 is" and "not knowing anything" indicate that Blaine felt that he just didn't know enough about the GlowScript syntax to deal with the computation.

Otto had a similar, though less severe, reaction to getting stuck on using GlowScript. He discussed the process of figuring out the relevant physics but not being able to translate his ideas into code.

OTTO The electron moving through the magnetic field... I know what direction it should be moving and everything, how its velocity should be affecting everything. But I don't know how to put that into computer words... Even when I know what should be happening, it just wasn't happening, because I don't know how to use GlowScript that well.

He explained the roadblock: "I don't not know how to use GlowScript that well." Though his programming inexperience is what prevented him from succeeding, Otto acknowledged that he DID know the ins and outs of the non-computational part of the physics problem. He contrasted what he did and did not know, saying, "but I don't know how to put that into computer words." Otto's experience was different from Blaine's because Otto was able to identify what he knew about the problem and what exactly he got stuck on. This indicates that the challenge of interpreting code can be different based on the student and the context, but in both cases it presented a barrier all the same.

Circe also described her challenges with understanding the code. She would start a computational activity and immediately feel lost.

> CIRCE I feel like something like coding can't help you understand physics better if you don't understand what the code means in general. He gives us the code to start off with, but none of us really understand what that means. So we look at [the starter code] and we're like, 'what does any of that mean?' So then you add things to that, but you don't understand why.

She often did not understand the program, or starter code, that Mr. Buford distributed to be worked on. This had the effect of preventing Circe from learning physics through computation. She even described attempting to engage with the activity and add her own code but feeling completely confused and directionless. Her understanding of the computation was that success depends on computational literacy of GlowScript, and some students don't have the tools to engage on that level. Her use of "we" indicates this experience of confusion is shared among peers.

Even for students who had seen programming before, using the GlowScript program, structures and syntax was still a challenge. For example, Otto had taken a physics class and a computer science class before enrolling in Mr. Buford's class. Despite these experiences with the "ingredients" of computation-integrated physics, Otto still felt like Mr. Buford's version of computation was new.

> OTTO It's a lot more *physical* in GlowScript because in the other class I took with coding, it was more just data and lists and whatever. But this you're having a particle moving through whatever so you have to use like vectors and all that. That's new to me. I haven't done anything involving movement and displays and that.

He said GlowScript physics was unique because of the movement and the visual nature of the activity, whereas computer science was about "data and lists." Computation in physics felt totally new to him, from the language (GlowScript) to the conceptual features (e.g., vectors, movement, animation). Doing computation with GlowScript was different from both physics *and* computer science, and this unfamiliarity made it difficult for him. The difficulty manifested when he had to combine physics with computation: "I know what direction it should be moving and everything, how its velocity should be affecting everything. But I don't know how to put that into computer words."

For Otto, who had prior experience with both physics and computer science, working with GlowScript still felt totally new, and he found it difficult to put what he knew into "computer words." This indicates that interpreting code may be a significant challenge for all the students at some level and that prior experiences with code do not directly translate for students. Otto points to the specific features of the integrated physics-computation format (making particles move, using vectors, making displayed simulations) that were still a challenge for him. Just because he had the separate physics and computation pieces, did not mean that Otto knew how to combine them, and he still struggled with translating the ideas into the "computer words."

Blaine, Otto, and Circe all shared how they got stuck because of a difficulty with the computer program, not the physics concepts. The impact is twofold. First, it stops students in their tracks when they do not know how to deal with code during a computational activity. Second, it can cause a negative affective response, like Blaine's self-evaluation ("I don't know anything!") or Circe's indictment of the activity itself ("coding can't help you understand physics better if you don't understand what the code means").

6.6.6 Contextual Challenges

There were also some contextual challenges that students faced in Mr. Buford's class. Unlike the previously discussed challenges, these are related more to the specific implementation of the computational activities and pedagogical choices made by Mr. Buford. We share these, not as a critique of Mr. Buford's implementation, but as a way to illustrate the variety of challenges (even those that are unanticipated) that can arise for students and how those depend on the context.

6.6.6.1 Assessment and Motivation

In Mr. Buford's class, the computational activities were not graded intentionally. Mr. Buford felt that since the activities were new and not explicitly a part of the AP curriculum, they could go ungraded and simply serve as opportunities for students to engage with physics concepts more deeply than they normally would. He explicitly said in his interview that "You don't have to get something for every little bit of effort that you make, so it can be its own reward," showing that he viewed the computation problems as intrinsically motivating.

In the interviews with students, we did see that students understood this motivation and experienced it for themselves at times. For example, Ed expressed a similarly productive view of computation, that the purpose was to get a better grasp on programming concepts, which in turn helped her see the connection between formulas and actual physics phenomena. We provide the excerpt below.

> ED And just seeing how just changing a couple of numbers could change the entirety of the coding was interesting... That was helpful for me to get the whole concept of coding.

However, at a different point in the interview, she articulated a much bleaker view of what computation was all about, referencing the grading policy.

> ED [Coding activities] are just really tedious. When I'm doing it, I just feel like there's something else I could be doing... I feel like coding is like something you kind of know... and it just feels kind of like busy work, but not busy work that he's going to grade, so it just feels useless.

The goal of computation, as Ed articulated here, was nothing! Because it was not graded, there was no point in engaging. The computation was "tedious...busy-work" which made Ed want to disengage even more. Had the activities been graded, she may still have found them tedious, but the fact that they were ungraded meant they were "useless", in Ed's view.

Ed's frustration at computation did not last throughout her interview, but the above excerpt demonstrates that the ungraded nature of computation in Mr. Buford's class can contribute to a feeling that computational activities serve no purpose. Feelings like this can impact students' motivation ("feels useless"), and given the open-ended design of many computational problems, motivation is needed in order for students to be willing to explore the activities.

As Mr. Buford indicates, it is perfectly reasonable to not have every single activity be graded or externally motivated. In fact, we could imagine several arguments for leaving computational activities ungraded. For example, teachers may want to reduce the pressure and stress of grades while students are doing a novel, unfamiliar task. However, as Ed's response indicates, there is a strong need for messaging about why students are asked to complete an ungraded activity, why the activity is not graded, and why they should still be motivated to complete the activity.

6.6.6.2 Solutions and "Right" Answers

When introducing the computational activities, Mr. Buford would explain the minimally working program and show students what the output of the code should be when fully working (either by drawing it on the whiteboard or showing the output from his solution code). He intended this as a way to show students what the end product should be in an otherwise very open-ended activity. Mr. Buford was very careful in his explanations to emphasize that there could be multiple right answers or solution paths to the computational activities.

Despite his caution and explanation of multiple paths, knowing that Mr. Buford had a "correct solution" posed an affective challenge for some of his students. For example, Circe was a student who viewed "success" at the computational activity as "being right," and she complained that her own ideas were always "wrong" when it came to computation. Below, the interviewer (Hamerski) asked her about this view.

INTERVIEWER How do you know it's just wrong?

CIRCE Because you see the answers. I guess there's multiple answers, so you might not be completely wrong...but the one that we're given, or the one that the smartest kid in class figures out is different than the ones that we had.

She articulated that the goal was to get the answer that the teacher has or the smartest kid in class had. Anything else she saw as "wrong." She even acknowledged that there could have been multiple solution paths, but she still interpreted a mismatch in her answers as "not completely wrong" and set up this comparison for her work versus a "smartest" or "given" (teacher's) solution. Circe reasons that "because you see the answers," hers (which do not match) must be wrong.

From this perspective, showing the final output to the class may inhibit students' ability to see paths beyond the one they are shown and may pose an affective challenge for students who need to reckon with the tension between being right and engaging openly with the problem. This desire to be right also can prevent students from exploring the problem setting and making mistakes from which they can learn important aspects of the problem.

That said, we do not know what would have happened if Mr. Buford did not provide the output for the computation problems. Without knowing the output, students could struggle more with interpreting the code or may encounter more setbacks as they work through the open-ended problems. These contextual challenges are directly related to choices that Mr. Buford made in his implementation of computation-integrated physics; however, they do not represent all the contextual challenges that students could face. More studies should be done in a variety of contexts that look at students' contextual and environmental challenges.

6.7 Connection Between Challenges and Theory

From students' interviews, we see that they faced a variety of challenges when computation was integrated into their physics class. While it was not the explicit focus of this study, the students' statements point to theoretical constructs in education research that may better help us to understand students' experiences and how to help students address these challenges in the classroom. Specifically, we found ties between students' comments, their mindset, self-concept, and self-efficacy.

Briefly, self-efficacy is a person's belief in their own ability to complete a task [113, 112]. Within the context of a computationally integrated physics classroom, self-efficacy would address the question of "how well can I do computation in this physics class?" Mindset, on the other hand, is a person's belief in their ability to change their own traits/competencies [2]; thus, mindset would address the question of "how much can I improve at doing computation?" In contrast, self-concept is "a person's perception of self...inferred from their responses to situations" (page 411) [119]. Rather than being task related (as self-efficacy), self-concept is in relation to an entire subject area. This would address the question of "how is doing computation related to me?" In the subsections below, we further outline each of these constructs and how they are related to our data. We then discuss the overlaps in these constructs and the implications for instructors and researchers.

6.7.1 Self-efficacy

Originally developed by Bandura, self-efficacy is "concerned with judgments of how well one can execute courses of action required to deal with prospective situations" [112]. In discussing how self-efficacy relates to students, Bandura suggested that it contributes to motivation and confidence within a given academic subject: "The higher the students' beliefs in their efficacy to regulate their motivation and learning activities, the more assured they are in their efficacy to master academic subjects" (page 18) [113].

Since its introduction, self-efficacy has been broken down into four sources: mastery experiences, vicarious learning, social persuasion, and physiological state [113]. We looked at how the four sources have been used in STEM education research to gain a deeper view of what they could mean for a computationally integrated physics context [104, 105]. Mastery experiences refer to the impact of successes and failure: "successes heighten perceived self-efficacy; repeated failures lower it, especially if failures occur early in the course of events and do not reflect lack of effort or adverse external circumstances" [113]. In our case, completing a coding task could count as a mastery experience, or receiving an error message from the coding program could be seen as a "failure." Vicarious learning is when a student makes an adjustment to their self-efficacy after witnessing a peer's performance. For example, a peer's success at a computational task can raise self-efficacy if the student then thinks they can succeed too, but seeing a peer fail despite effort can lower the observer's self-efficacy for related computational tasks. Social persuasion is about external appraisals of ability that a student then internalizes into their self-efficacy. Evaluations can come from peers, authority figures, or other participants in the domain where the student must perform. Social persuasion need not be verbal or direct, and its effect depends mainly on how the student perceives it. Physiological state refers mainly to stress "as an ominous sign of vulnerability to dysfunction" [113]. Students, when they are stressed, expect to perform worse, whereas when they are calm and clear-headed they may feel a boost to self-efficacy.

A few examples from computation education research show how self-efficacy can be used in computational settings and how it can reveal information about student learning. Self-efficacy was employed by Lishinski et al [92], who viewed self-efficacy as a reciprocal feedback loop, where self-efficacy judgments based on affective responses can have a long term effect on learning outcomes. The authors found that previous programming experiences impacted future performance in part due the effect that past experiences had on self-efficacy, whether positive or negative. Kinnunen and Simon [93] used self-efficacy to describe students' affective responses to a computational assignment in an introductory-level university computer science class. When students made an affective self-assessment, the authors were able to describe it in terms of self-efficacy, indicating a connection between self-efficacy and the act of affect-based evaluations of oneself. In a follow-up study [94], Kinnunen and Simon used the four sources [113] to understand how self-efficacy was tied to experiences that students had in the course. They also considered in their framework how self-efficacy could evolve in response to experiences and what could set this evolution in motion. A year later, the same authors [95] returned to self-efficacy, this time using it to describe emotionally charged events they observed where students evaluated their own abilities and consequently altered or reinforced their self-efficacy for programming. The evolution of how Kinnunen and Simon [93, 94, 95] used self-efficacy to explore programming experiences demonstrates a precedent for connecting self-efficacy (and its sources) to computation.

We can see these sources of self-efficacy in our data, with examples that may be either contributing to or degrading students' self-efficacy in computation. For example, in our Responses to Setbacks challenge, we saw Blaine, Ed, and Otto take on very different responses when faced with confusion and uncertainty in the coding activities. Otto demonstrated a notable persistence in his approach to the problems, experienced multiple successes (mastery experiences) with the computation problems, and often said high self-efficacy statements like "I can implement that". On the other end of the spectrum, Blaine experienced very few mastery experiences, which led to a very negative self-efficacy with regards to coding. We see him say "I can't do this shit" and "I don't really try to do any more cause I'll put in a hundred things and then I'll just get a black screen or I'll get some error," which directly tie his lack of success ('blank screen' or "get some error") to his belief that he can't code or can't make progress. That said, Ed's experience demonstrates that mastery experiences are not all or nothing. Ed did have some moments of success with the code, but she indicates that it's only one in three activities. However, even those moments of success made her feel like she could code and contributed to her belief that "you finished that one, you can probably do all of these". All three of these students point to the importance of mastery experiences in their self-efficacy, especially Ed's case, which highlights that not all of the experiences need to be successful.

We can also see indications of the other sources of self-efficacy in our data. For example, Joyce references the stereotype of a "fast coder" in her statements in the Unbelonging and Stereotypes challenge, saying that she was simply average because she couldn't "just look at the scenario and just code it in five minutes." Even though Mr. Buford never set any expectations about how fast students were expected to code, Joyce still had this idea that the good coders were able to just look at the code and do it, which may come from societal stereotypes, media portrayals of programmers, interactions with peers, and other forms of social persuasion. Ultimately, this influences how Joyce sees herself and how she evaluates her skill. We also see Circe and Ed describe coding as a stressful, frustrating activity in the Stress/Frustration challenge. This outlines one of the physiological states that can contribute to self-efficacy. If a student's experiences of coding are all taking place in a highly stressful, tense physiological state, then that contributes to their negative self-efficacy and inability to complete the task. We see this with Circe, who directly states that she's "not going to put [herself] through that" because the programming is "just unnecessary stress."

The sources of self-efficacy open questions for additional research in computationally integrated classrooms. For example, what tasks and what grain-size lead to mastery experiences? Does interpreting an error message successfully count as a mastery experience or does the whole program have to be completed for students to feel successful? How can we as instructors and facilitators help students see their success in each of these moments? How can we help students approach computation without a stressful physiological response, while at the same time not seeing computation as "useless" or "busy work"? At this point, we do not have answers to these questions, but our results from the challenges students face would indicate that more research is needed in this area.

6.7.2 Mindset

Dweck [2] defined mindset in terms of self-beliefs about the mutability of abilities and delineated between fixed mindsets and growth mindsets. She argued that a fixed mindset is detrimental to learning because students with this mindset lose motivation more easily and they are harsher judges of self when faced with adversity. On the other hand, students with a growth mindset build motivation to improve when they experience failures. Blackwell et al [4] provided a review of perspectives a student would hold depending on their mindset. The most fundamental perspective is that someone with a growth mindset believes they can improve their intelligence through effort, whereas someone with a fixed mindset believes intelligence is unchangeable. Students with a growth mindset study to learn, see mistakes as learning opportunities, believe that effort is good because it makes you smarter, and see knowledge as something that can be worked for [2, 4]. Students with a fixed mindset study to prove their smarts or superiority, avoid mistakes for fear of being seen as stupid, believe that too much effort signifies lack of intelligence, and see knowledge as something that comes from authority figures [2, 4]. When students fail, the ones with growth mindsets believe they need to study harder and better, whereas those with fixed mindsets believe they failed because they are stupid or because the assessment was unfair. As a disclaimer, mindsets are flexible and able to change, meaning one isn't forever a "fixed mindset" person [2]. Also, mindsets can vary between contexts or even within a single context, meaning people can hold both growth and fixed mindsets about different subject matters or even at the same time [2].

From the literature, mindset has been used in some initial studies to describe students' approaches to computation. In one study, Scott and Ghinea [106] set out to discover whether programming-specific mindset could be differentiated from general mindset for school. They discovered that the unique nature of programming activities led students to develop a specific mindset for programming, different from a more general, school-based mindset. To track learning in connection with mindset, an intervention study was devised by Cutts et al [107]. They intervened in an introductory university programming class by having tutors teach mindset-related strategies. The issue of stuckness was focal: the students' mindsets hinged on whether they attributed stuckness to internal factors (leading to fixed mindset) or external factors (leading to growth mindset). These findings suggest that mindset could change or even develop anew when computation gets introduced into a physics curriculum. Lodi [108] performed a similar study to Cutts et al [107], but he focused on high school students and sought to understand how the computer science curriculum impacted mindset. He argued that students with learning-oriented goals (e.g., aiming to learn and be challenged) aligned with a growth mindset, whereas students with performance oriented goals (e.g., aiming to score well and avoid challenges) aligned with a fixed mindset. These studies highlighted some of the same features of mindset that emerged from Dweck [2] and Blackwell et al [4], which gives us precedent for applying these theories to a computation education setting.

In our data, we saw similar perspectives mirrored in how students articulated challenges in Mr. Buford's class. For example, in the Contextual Challenges section, Circe displayed both a desire to be right and the desire to look to the teacher for answers, which aligns with the fixed mindset tendency to look to authority/expert figures (like teachers) as the only trusted source of knowledge. Individuals with fixed mindset tend to value accomplishments and grades because they signify high intelligence, whereas growth mindset people value learning because that is what actually *improves* intelligence. Circe articulated a tendency to consult the teacher's solution to see if hers was right, which represents a potential challenge in other settings where computational activities are designed to have multiple solutions and unanswered questions built into the learning process. For students who tend towards a fixed mindset, this design is rife with barriers to success.

Another example comes from Unbelonging and Stereotypes and Strain on Physics Knowledge, where we observed Circe and Ed provide similar views about feeling out of place or not knowing how to proceed when confronted with computational challenges. For Circe, feeling out of place was tied with her belief that being "really good at physics and coding" meant having "the same kind of brain." When students take up the view that they need to be built a certain way in order to succeed at physics and/or computation, they are aligning with a fixed mindset, which at its core says that intelligence is an inherent characteristic and impossible to change. For Ed, she felt that her understanding of physics was questioned or alienated when she had to do physics with computational tools, to the point that she believed she "just [thought] about [the material] in a different way," and she emphasized the computation was only strange *for her*. This distancing that Ed does indicates that the challenge was related to fixed mindset, because she was cementing that her way of thinking was not meant for computation rather than seeing the difference as a growth opportunity.

Lastly, we return to Responses to Setbacks to compare the mindsets Otto and Blaine seemed to take up when faced with setbacks. The difference in persistence points to a difference in mindset. Both students articulated a point of confusion or stuckness, but Otto's response was to embrace the challenge ("I'll start working through it, I'll try to simplify it"), whereas Blaine's response was to give up ("I don't really try to do any more"). For Otto, the setback was an opportunity to learn, which aligns with a growth mindset, whereas for Blaine, the setback was paralyzing, which aligns with a fixed mindset. The contrast between how students respond to these challenges is closely aligned with mindset theory, which indicates that mindset is key in whether students succeed at overcoming challenges in Mr. Buford's computational activities.

Our work suggests building on the premise that mindset is linked to how students respond to computational challenges. For example, how do students develop their mindsets for computational work? Are there pivotal experiences (like mastery experiences for self-efficacy) that impact students' mindsets in significant ways? Our data would also suggest observing how students treat computational challenges differently in the wake of mindset interventions, similar to many others' recommendations [124, 125, 126, 127, 128]. We also recommend studies on how developing mindset could help students in other ways in a computationally integrated physics context. We do not have the answers, but our results from the challenges students face would indicate that more research is needed in this area.

6.7.3 Self-concept

Shavelson et al [119] emphasized that self-concept is organized, or structured by domain, meaning that a person has a different self-view depending on the context (e.g., physics class) and focus (e.g., computational activities). It is developmental, in that a person builds or develops a narrative about oneself in a particular set of contexts. Though it was at first used to describe broad self-views (i.e., self-esteem), self-concept was only later used to examine academic realms. Marsh and Craven [118] argued that what distinguishes academic self-concept is that students evaluate their performance in comparison to their performance in other domains, their peers' performances, and their internal standards of performance quality. Though focused on evaluation, it is distinguished from self-efficacy because the evaluation of performance is stabilized by previous evaluations and exists broadly for an entire school subject, whereas a self-efficacy judgment has more to do with prospective situations in a given academic domain. This would make the difference between self-concept and self-efficacy threefold: (1) domain-level versus task-level evaluation (2) evaluation of past performance versus prospective performance, and (3) incorporation of evaluation into a sense of self versus a sense of ability.

In a theory-building paper by Brunner et al [120], they propose and evaluate the effectiveness of a model for self-concept. The authors suggest using a first-order model (e.g., focusing broadly on academic self-concept) or a nested model (e.g., considering broad academic self-concept AND math self-concept). They emphasize that self-concept can be split into separate self-concepts for each academic domain when using the nested model. In our context, this would indicate that this model of self-concept would be appropriate for the students who perceive computation as a separate domain from physics (not integrated *into* the domain of physics as a learning tool). This is in opposition to how Mr. Buford, the teacher, framed computation in his classroom.

While self-concept has not been used in computation research, there have been examples in other areas of education research. For instance, Chen and Xu [111] studied self-concept for junior high school English and its components: listening, speaking, reading, and writing. The qualitative case study of multiple students demonstrated how students with different self-concepts for different components can have drastically different trajectories in class, pointing to the complicated nature of self-concept for specific academic domains and activities. Espinosa [109] produced a quantitative study about cataloguing a variety of factors that build into academic STEM self-concept for college students. The core of her methods addressed self-concept from its most basic definition: evaluation of oneself. Mardiningrum [110] produced a case study on two participants in a university student theater club. The collaborative nature of this environment made social interaction a focal aspect of the participants' self-concepts. In a learning environment that uses group-based computation activities, we would expect social interaction to contribute to self-concept.

The studies above provide insight for how we might apply self-concept to a computationally integrated physics setting. The construct has not been used in this type of environment before, but we know that in order to apply it we need to focus on moments of self-evaluation [109], accounts of social interactions [110], and the nuances in how students see themselves in relation to computational activities, computation, and physics as a whole [120, 111]. This construct adds to our study because it can help us frame the way students discuss their feelings about computational experiences in a way that involves perceiving their role, as opposed to perceiving their ability (self-efficacy) or perceiving the malleability of their role and/or ability (mindset).

For example, in Unbelonging and Stereotypes, Circe articulated that computation "doesn't make

[her] feel like [she] belongs in physics." When students feel that they don't belong in a computation-integrated physics environment, they can also feel that they weren't MEANT to belong there, as evidenced by Circe's later reflection on not having the brain for computation: "I have a lot of friends who are really good at coding...I guess it's all the same kind of brain." This feeling is related to self-concept because it could be framed as a perception of self in relation to a school subject. Feeling out of place in comparison to peers is part of self-concept [119]. The challenge lies in the potential for students to feel this way and lose interest in physics before gaining a realistic view of what it means to *do* physics.

Another challenge tied up with self-concept is Interpreting Code. Blaine lamented in this section about his inability to understand what the code meant. For Blaine, it was about being unable to make any progress on the activity and being unable to interpret error messages. These roadblocks produced an affective response: Blaine said, "I don't know anything!" This evaluation of self in relation to computation indicates a self-concept judgment. Blaine felt stupid when doing computation.

Similarly, we see Blaine's low self-concept in his Responses to Setbacks. Here, he outlined his pattern of failure, which we view as an accumulation of negative experiences. Accumulations and patterns of experience are part of how a student builds self-concept for a school subject [119, 118]. Blaine is a student who has identified a pattern in his computational experiences: "I don't really try to do any more cause I'll put in a hundred things and then I'll just get a blank screen or I'll get some error." The repeated roadblocks with no success at overcoming them has led Blaine to believe he "literally can't get anything but a blank screen." No matter the circumstance, he has experienced computation enough to develop and hold this belief. Blaine's self-concept is tied to this challenge because the negative self-concept is a result of this pattern. It is important to acknowledge the ramifications when students deal with challenges unsuccessfully like this, one consequence being the harm to self-concept.

As a final example, we look at Ed's delineation between physics and computation in Stress/Frustration and Strain on Physics Knowledge. In these sections, Ed said that the way she thinks about physics “can’t be programmed.” This sends the message that not all physics knowledge is meant for a computer program, in particular Ed’s physics knowledge is not meant for a computer program. One possible explanation for this belief is that when Ed encountered a new, difficult type of physics (i.e., physics through computation) Ed protected her physics self-concept by building a separate, low self-concept for computational endeavors (or “GlowScript”, “coding”, etc.). This separation can mean that some students don’t let themselves develop as doers of computation, and it can prevent them from learning on days when this is an aspect of their physics class.

Self-concept suggests that students can develop a view of themselves in physics that is different from the view of themselves when doing computational activities, which validates the possibility of Ed’s experience with separating the two domains. Since self-concept has not been applied to computationally integrated physics before, our work indicates it may be a viable lens for understanding how students are internalizing their experiences in computation. For example, future work could point to the process by which self-concept develops in these settings, how students are reconciling their views of the two different domains (physics and computation), and how that fits in with their larger academic self-concept.

6.7.4 Intersection of Self-efficacy, Mindset, and Self-concept

In talking about the challenges that they faced, the students in our data made statements that point to their self-efficacy, mindset, and self-concept. While we previously discussed these constructs as separate ideas, we want to emphasize that these are not independent theories or constructs. In fact, the overlap between these constructs illuminates avenues for future research, curriculum design, and pedagogy.

For example, we can see aspects of all three constructs in how Blaine faces the Responses to Setbacks challenge. Blaine described how he experienced a series of failures related to doing computation: “I literally can’t get anything but a blank screen...I’ll put in a hundred things and then I’ll just get a blank screen or I’ll get some error.” These failures fit narratives about the development of negative self-efficacy and negative self-concept, and the way Blaine articulates them aligns with the language of fixed mindset. Each framing provides different insight into Blaine's experience. The self-efficacy framing shows us the deep impact of serial negative mastery experiences for developing self-efficacy, as shown when he described how he felt that he "literally can't get anything but a blank screen" after repeatedly failing to make progress in the computational activity. The self-concept framing shows us how a pattern of negative experiences can come to define what computation means to a student, as shown when Blaine expressed apathy when describing his relationship with computation: "I just don't even care. I'm like 'whatever dude. I can't do this shit." The mindset framing shows us how a fixed mindset can be closely tied to a series of computational failures, specifically no change in approach in response to the failures: "I don't really try to do any more cause I'll put in a hundred things and then I'll just get a blank screen or I'll get some error." From this one example, we can see that the three frameworks overlap and build into one another. Blaine's build-up of failures without learning from them aligns with a fixed mindset, and their accumulation led to a perspective that could be viewed as low self-efficacy or low-self-concept for computation.

This illustrates how the theoretical lenses can overlap and provide a fuller picture of the impact that the affect-based challenges can have on students. We use all three to highlight different views on the same individual experiences, but they provide varied angles from which to understand what is going on with the students in our study. That said, this study only provides an initial window into how these frameworks relate to one another, and we suggest future research specifically focus on how each framework fits with one another in this context, how theory-based interventions may impact students' perceptions, and how these frameworks may be leveraged to better understand computation-integrated classrooms. We view the presence of many angles as a way to identify jumping-off points for further research on affect-based learning and challenges, which is sorely needed and which we highlight in the discussion section. However, we first highlight some positive experiences that students recounted in their interviews. These did not fit in with our challenges, but still provide a unique perspective on what students experience and how computation can be beneficial, according to students.

6.8 Positive Student Experiences

Along with the challenges students faced and recalled in their interviews, there were also indications of positive experiences brought on by computation. In this section, we outline a handful of beneficial impacts of computational integration that students interpreted. Afterwards, we discuss how they relate to some of the goals that Mr. Buford set out to achieve by introducing computational activities to his class.

We begin with a comment from Ed that demonstrates how she learned about using computation to see physics. She describes getting "the whole concept of coding" through engaging in a computational activity about collision physics.

> ED We were doing momentum, and we were looking at elastic and elastic collisions, and we actually coded something where two blocks had to collide. And just seeing how just changing a couple of numbers could change the entirety of the coding was interesting... That was helpful for me to get the whole concept of coding.

Ed came to understand how changing numbers in the program is connected to seeing the physical consequence in the animation. Computation allowed her to make small changes to the program and to see the relationship between momentum and the actual movement of objects. Ed's articulation of this and engagement at this level suggests an orientation towards learning physics through computation rather than just trying to get through the activity. Though she outlined many challenges in the previous section, this comment shows that students also see benefits to computation, and one of those benefits is the visualization and strengthening of physics concepts.

Joyce expressed a similar perspective, which was that the process of translating ideas into code was a way of learning physics concepts. While Ed focused on the benefits of interacting with the dynamic, completed code, Joyce discussed how creating code was constructive for her.

JOYCE By actually coding the formula and what variables go in, I think it helps in learning the concepts. It's just you may not catch [an error] at first and you might mess up because we were supposed to put other stuff in [the program].

Joyce shares how she felt like learned the physics concepts better by coding the formulas and variables. In the second part of her quote, Joyce talked about the experience of accidentally letting a bug, or coding error, get into the program ("we were supposed to put other stuff in the program") and prevent it from running properly. By relating learning physics concepts to the debugging process, Joyce demonstrates that she understands there is value in meticulously translating physics formulas into code and incorporating the computer's feedback. This awareness allowed her to engage with the activities in a way where she felt that they helped her learn physics.

Finally, we found computation can help some students build interest in physics. Beck discussed at length how he viewed computation as an opportunity to connect with physics in a more authentic way. Below, he talked about how a visual world of physics opened up when he used GlowScript.

BECK GlowScript provided even more visuals and stuff to actually connect with, which is what made me understand physics and like it even better. The visuals, the demonstrations, that ability to see the things in real life... they just helped provide even more for that, and they even strengthened my liking for physics even more.

He connected with the visuals and felt as if he were seeing the phenomenon in real life. Beck went on to say more about the benefit of computation, describing how it provides an opportunity to do some of the same activities that physicists do professionally.

BECK [Coding] allows you to apply stuff that you've learned in a way that's different from just solving a problem on paper, because you actually get to see the result of what you've solved in real life. I mean it's a computer, but you get to see it actually work. It gives you a view of what physicists do, I suppose. Like you get a problem and you use physics to solve the problem, then you see it actually work... I like the coding in physics because of that.

In this excerpt, Beck saw the purpose of computation as seeing a physics problem at work in a simulation of the real world. It was a way for him to connect what he was learning to what was relevant to him. It was also a way to understand the type of work that actual physicists do. In Beck's case, this engendered an interest in him saying "I like the coding in physics" and "[it] strengthened my liking for physics even more." This shows that computation has the potential to help students build an interest in authentic physics as well as help with learning.

The benefits that Ed, Joyce, and Beck described are similar to some of the goals that Mr. Buford had for his computational integration. In particular, he had wanted students to strengthen their understanding of physics concepts through computation, saying, "I hope it just enhances them thinking about the physics concept that we're trying to learn, ideally....I feel like when you're writing the code for this, you have to understand how projectile motion works, or you can't write code that models that very well." Both Ed and Joyce described the benefit to conceptual understanding, though it's not clear whether Mr. Buford envisioned the same mechanisms of learning. For Ed, she learned through interacting with the completed code, and for Joyce, learning happened through creating the code itself and working through bugs. The benefit that Beck described goes beyond what Mr. Buford said, namely the computation helps him do *real* physics and builds his interest in the subject.

There were also some ideas that were missing from student interviews, benefits that Mr. Buford envisioned but that did not seem to bear out in our data. Mr. Buford had hoped that the open-ended nature of the computational activities and the choice to not grade them would spur students to be more creative, given that a lot of the constraints on traditional physics projects were stripped away. Students did not seem to latch onto the creative freedom in their interviews, so it's unclear to what degree this goal was present in the actual implementation. Also, there remains the question of what benefits could exist in other implementations. For example, Mr. Buford wondered whether "you could use [computation] as a way of developing concepts" rather than just reinforcing. With different design goals and in different contexts, this may be entirely possible, which could chain into students seeing different benefits to the computational integration.

6.9 Discussion

From students' interviews, we see that they faced a variety of challenges when computation was integrated into their physics class. Some of these challenges were related specifically to code (e.g., Interpreting Code, Responses to Setbacks), while others were related to the pedagogy and culture of the classroom (e.g. Contextual Challenges), but many of them were unique or had unique components due to the integrated physics classroom context (e.g. Strain on Physics Knowledge, Unbelonging and Stereotypes, Stress/Frustration).

The challenges that we found specifically related to code (Interpreting Code and Responses to Setbacks) are similar to the student challenges reported from computer science contexts. Jenkins [177] highlighted barriers in introductory level computer science learning, mainly focusing on the extra skills that students need to learn to engage with computation, such as syntax, semantics, and algorithms. He argued that what made computation hard was mainly the novelty of it. This aligns with what we found in Mr. Buford's computationally-integrated physics class. For example, a part of Interpreting Code is understanding syntax and how it pieces together as well as error messages and strategies for addressing them. These are new skills that students did not encounter before unless they took a computer science class. Even then, we found that students who *had* taken a computer science course still struggled with the syntax and idiosyncrasies of Glowscript. Previous research by Bumler et al [193] found that students with prior computational experiences did not view minimally working programs using the GlowScript platform as authentic computation. The conflict between their previous experiences and the lack of utility of students' previous experiences in the context of this research implies there are difficulties transferring practice to the GlowScript platform. The basis for this disconnect between platforms and contexts needs to be studied in greater detail. This also speaks to the Responses to Setbacks challenge because the process of learning a programming language (especially debugging) requires persisting through many mistakes and learning from them. This parallels another study, in which Bosse and Gerosa [91] catalogued some of the main worries that students tend to have in programming settings, including trouble with syntax, variables, error messages, and code comprehension. The worries were sometimes so overwhelming that when a student realized their code contained an error, they were more likely to give up. We saw a similar case with Blaine, who gave up after encountering numerous errors and no longer proceeded with the activity. From another perspective, Svensson et al [183] viewed computation as a social semiotic, or a way of communicating about and exploring phenomena. They saw challenges emerge when students had limited skill with using the semiotic resources, even when students *did* see the benefit of communicating and exploring through computation. This mirrors the experiences of Ed and Otto, who both saw the usefulness of computation and often even knew the relevant physics concepts, but they ran into roadblocks because they had limited skill with computation itself and/or GlowScript. The fact that we saw the same challenges and barriers in the computation-integrated environment that are seen in computer science contexts indicates that students' interpretation of code is a broader challenge for any type of coding activity. Given the common challenge between contexts, this would indicate a place where computer science educators and physics educators can learn from one another about how to best support students.

However, we also found several challenges that were unique to the computation-integrated physics environment. For example, in the Strain on Physics Knowledge challenge, we saw that Ed was separating the domains of computation and physics, so that her difficulty with computation would not affect her view of her physics competence. She would reassure herself that "You know [the physics], you just think about it in a different way, but that's not a way that can be programmed on the platform." This challenge is unique to the computationally integrated physics environment, specifically because we have merged two subjects that for these students would be viewed as two separate domains. In a separate computer science course, students' physics abilities and self-concept would typically not be threatened or involved at all. However, because of the integration, we see some students protecting one view of themselves, potentially at the cost of the other. In the case of Circe, the integration of computation led to statements of unbelonging and a distancing of herself from physics as a whole. In the case of Blaine, we saw that multiple failures at the computational activities led to negative self-efficacy statements and a low self-concept when he said, “I don’t know anything!”. This is similar to what Lishinski et al [92] found during computational activities, namely that negative self-efficacy judgments can lead students to use tactics that harm their learning rather than help.

The integration of computation into STEM is strongly motivated, including arguments about preparation for students’ future careers and making STEM courses more relevant. However, we see students intentionally separating the domains. This would indicate to teachers, researchers, and curriculum developers that more attention needs to be directed to *how* this integration occurs. For example, as part of the ICSAM workshop, Mr. Buford was altering an existing curriculum. He already had lesson plans to teach all the necessary physics content, and perhaps it made more sense to introduce computation at the transition points in the curriculum rather than potentially disrupt the material mid-concept. Additionally, ICSAM teachers learned how to program with GlowScript during a summer workshop. They were already physics experts when they arrived, but many were novices at computation, meaning they learned to program as a way of modelling and exploring what they already knew about physics. This process could have transferred to how their students would go on to learn computation in their classrooms: physics first, computation later. Ultimately this could have contributed to the separation of computation and physics as separate domains. That said, there is certainly a precedent for integrating STEM domains. After all, physics and math have been closely tied since the foundation of the field. We don’t think twice about whether formulas and calculations are a part of physics, and for students, learning to use math as a tool and learning physics go hand-in-hand. In the same way, we envision a future where computation is also treated as an everyday tool for learning physics in classrooms and viewed as such by students, but we need to learn more about what is happening in these integrated classrooms. However, the math and science domains are blended at a much earlier point in a student’s schooling. Students perceiving computation and physics as two different domains highlights the need to investigate whether integrating at an earlier point in a student’s science careers would impact their perceptions of computation being a tool for doing science.

Another challenge that is unique to the computationally integrated contexts is the balancing of content between computation and physics. Given the other constraints that teachers are under (time limitations, science standards that must be met, etc.), it can be difficult to add computation to an already packed schedule. Mr. Buford commented in his interview that despite his natural curiosity for new ideas in physics, it was hard to try new things when he had to cover all the content on the AP Test. The year before he attended ICSAM, he simply saved computation for after the test was over in the last month of the school year. When he tried to integrate computation into his curriculum throughout the year, he just wasn't able to let the students slow down enough to wrestle with the computation and figure out how it could help them learn physics. For some students, the purpose of doing computation in physics just didn't stick with such little time. Furthermore, there may be some influence from the AP curriculum on what counts as "doing physics." Without changing the national expectations and standards to include computation, it will be near impossible to create fully integrated courses.

We also saw several challenges that were related to pedagogical choices from Mr. Buford. For example, Mr. Buford intentionally chose to not grade the computational activities, which led to Ed commenting that the activities felt like "busy work." He also chose to show the final output to the class, which often made Circe feel like her answers were "wrong" when they didn't match. In the Stress/Frustration part of analysis we highlighted how the students felt as though the activities being after the concept had been covered had framed them as causing undue stress. However, from Mr. Buford's perspective this was intentional because he thought introducing concepts via a computation activity would be too stressful. This catch-22 like outcome highlights the struggle that teachers face when making curriculum design decisions around integrating computation into their classrooms and highlights a desperate need for research focused on curriculum design for such environments. None of the above discussion points around pedagogical choices is intended as a critique of Mr. Buford (in fact he had strong pedagogical reasoning for his choices), but this highlights that there may be unique challenges depending on the specific implementation of computation-integrated physics and the classroom structures that a teacher employ.

For example, Beck described a positive structure in his interview from Mr. Buford's class. Beck came upon a roadblock and had to ask for help from Mr. Buford, who pointed out to him a built-in GlowScript that did *exactly* what he needed. In fact, having students ask for this function was part of Mr. Buford's plan—he confirmed after class to the researcher (Hamerski) that part of the activity's purpose was to discover the need for a new function. The challenge lies not in what we generated in the data, but in what was absent: the students who did not think to ask for help or who did not arrive at the point in the activity to realize the need for a special function. Students may struggle to ask for help for a variety of reasons. Students may feel intimidated by asking questions to an authority figure (their teacher in this case), they may feel too embarrassed by their "lack of progress" on the problem to ask for help, or they may struggle with social anxiety. Alternatively, and especially in a less collaborative context, students may have the impression from classroom norms or social stereotypes that they are supposed to be coding alone. Any of these reasons may prevent students from asking for help, and in turn, increase their frustration and perpetuate a negative view of computation.

As Mr. Buford confirmed, a teacher may let students struggle with an idea intentionally or may want students to discover an idea as part of the computational activity. With Beck, this worked well, and he was able to learn about the unit vector from Mr. Buford. However, for this to happen it was critical that Beck felt comfortable asking Mr. Buford for help and that Mr. Buford promoted that in his classroom. In another classroom context, with a different classroom culture, we could envision "Asking for Help" to be a challenge for students. This only points to the work that needs to be done to build on this study and examine the contextual challenges in other implementations of computation-integrated physics and other STEM courses.

6.10 Conclusions and Future Work

In this paper, we have described the student-perceived, affect-based challenges that high schoolers faced in a computation-integrated physics class: Stress/Frustration, Strain on Physics Knowledge, Unbelonging and Stereotypes, Responses to Setbacks, Interpreting Code, and Contextual Challenges. We also found connections between students' descriptions of the challenges and their self-efficacy, mindset, and self-concept. This work is laying the foundation for identifying affective barriers and those unique to computation-integrated STEM contexts, serving as the first study in this context to examine affective challenges from the student perspective. While this study is an initial step, more work needs to be done to understand the affective challenges students face and how to best support them.

An example of the importance of student perspectives from our data was when Joyce said she felt "just average" at coding when we were fleshing out the Unbelonging and Stereotypes challenge. She appeared to be one of the most competent programmers in class, but she didn't necessarily feel that way about herself. It is only through asking students about their experiences that we can find out how they feel about the challenges they face in class, and sometimes their answers can be unexpected.

To researchers, this study is a call to action. Computation-integrated physics courses continue to grow as computation becomes synonymous with doing STEM. With it come the complexities and difficulties of new curriculum and the need to understand the experiences of students in this new environment. We have found that the lenses of mindset, self-efficacy, and self-concept may offer meaningful insight into many student-based processes, yet there is a need for more exploration, particularly in how the integration takes form, how the protective separation of computation from physics can be minimized, and how the difficulties and frustrations of learning a new programming tool affect students. We need studies on affect, self-beliefs, and perceptions in computation-integrated contexts where computational learning is supported by design, where the curriculum is less constrained institutionally (e.g., regular instead of AP), where computational tools are the focus of the course, and where features of implementation support underrepresented students.

To practitioners, this study is a call to consider many factors when designing or altering curriculum for computational integration. We call for attending to the affect of students who take part in the curriculum, the tools being used to integrate computation, the pedagogical strategies for teaching computation, what it means to redesign existing curriculum, the curriculum's potential effect on students' perceptions of computation and physics, and the role computation can play pedagogically. But most importantly, practitioners need to extend grace to themselves as they figure out how computation best fits into the context of their physics course. We need to teach students authentic physics by using computational tools, but we also need to acknowledge the burden on physics teachers who are often saddled with altering curriculum to meet new educational demands, of which computational integration is the latest [72].

In conclusion, we highlight that the computational challenges raised in this paper need to be studied in more depth in the computation-integrated context as opposed to trying to understand them by only applying knowledge from physics or computer science education research. This type of curriculum is unique enough to warrant further studies, especially when considering the issues that arose when students had to deal with computation and physics at the same time in the same context. Computation in our physics courses is essential for the next generation of scientists, and it is imperative that we learn how to best apply computation as an educational tool to the benefit of our students.

6.11 Acknowledgments

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CHAPTER 7

DISPOSITIONS AND MINDSET IN COMPUTATION-INTEGRATED PHYSICS

This chapter builds on Chapter 6 by exploring the theory of mindset in more depth in the same context. Because of the breadth in students' perspectives and applications of theory in Chapter 6, I was able to design a study that focused on fewer theories but went more in depth, in part by incorporating more data sources. Specifically, I connected mindset to a theory that is more native to computation, computational thinking dispositions, and I devoted this chapter to fleshing out how these two theories show up in what students say and do in Mr. Buford's class. This is the last study in the dissertation, and it represents an operationalization of the research foundation I built in Chapter 6 and the research tools I honed throughout all the research described thus far in the dissertation.

7.1 Abstract

High school physics classrooms across the United States are making efforts to integrate computation into their approach to teaching physics. There is wide agreement on the importance of teaching computational thinking (CT) practices in these types of settings, but little research has focused on the dispositions that students can develop that support the development of CT practices. This study examines the case of one high school physics class where students do computation-integrated physics in a group work format. Drawing from a newly theorized framework on CT dispositions and the well-established theory of mindset, we investigate how students take up dispositions and mindset during class, and we examine connections between these theories and how they manifest in our data. We intend to help researchers and practitioners identify students' dispositions so that they can provide opportunities for their students to better develop dispositions and more productively engage with computationally integrated physics.

7.2 Introduction

In the last fifteen years, there have been multiple calls and reports for the integration of computation into both the high school and undergraduate physics curricula [33, 24, 182, 41, 194]. With each of these frameworks and reports, a strong emphasis has been placed on students developing Computational Thinking (CT) practices. Computational Thinking [129] is widely viewed as an important learning goal in STEM settings [130, 131]. It encompasses the practices and dispositions [132] associated with "solving problems, designing systems, and understanding human behavior, by drawing on the concepts fundamental to computer science" (page 33) [129]. Though it is based on ideas from computer science, CT is meant to be applied to situations with and without computers [129], designed as a set of developmental skills based on computing principles rather than actual computer skills. CT has been a part of the STEM education zeitgeist ever since Wing's conception and publication of it in 2006 [129]. Since then, there has been a widespread push to teach CT in STEM contexts, including at the K-12 level [170, 195, 171]. There is wide agreement on the importance of CT, but there is no clear consensus on how to support the development of these practices, especially in contexts where computation has been integrated into a STEM discipline [27]. One of the main focuses of curriculum designers and researchers has been CT practices [40, 133, 66, 196, 197], but there has been less of a focus on students' attitudes and mentalities needed to develop their CT practices.

The focus on practices in many of the instances of computational integration [40, 133, 66, 196, 197] fails to consider dispositions, which is the other half of ISTE and CSTA's [132] operational definition of CT. Dispositions is a term used to describe how students perceive and form attitudes about computational activities. Research has recognized the importance of incorporating student perspectives and affect into computationally integrated physics curriculum design [198, 70, 199]. The argument has been made that for students to develop and evolve their computational thinking practices then they need to have positive dispositions towards computation [132]. It follows then that a significant step in the successful incorporation of CT practice development in a curriculum is fostering positive CT dispositions. To date, dispositions have been understudied in comparison to the widespread research and implementation of CT practices, but they are just as important.

The focus on CT dispositions and not just CT practices can be traced to ISTE and CSTA's definition of CT [132], but it was recently incorporated into a detailed theoretical framework by Pérez [1]. Originally developed during a workshop series for secondary mathematics teachers, the Pérez's theoretical CT dispositions framework was situated in the context of a mathematics curriculum, which leaves the question open as to how this framework could be expanded into non-mathematics contexts. Nonetheless, Pérez's CT framework represents the most comprehensive published research on CT dispositions. We intend to extend Pérez's framework into the context of a computation-integrated physics classroom, with the goals of (1) demonstrating how the CT dispositions framework applies in a high school physics setting and (2) calling attention to the importance of CT dispositions in the widespread movement to integrate computation into physics curricula.

Previous research in computation-integrated physics classrooms has demonstrated that an important learning goal for teachers is for their students to foster high dispositions towards computational thinking [200]. In their study, Weller et al, produced a collection of teacher-articulated learning goals for computation-integrated physics learning. They found that teachers, although not using specific terminology of dispositions, wanted their students to have a positive experience with computation, experience a reduction in the intimidation of physics, and have a sense of accomplishment when they work through computational activities. Building on this work, Weller et al's [76] developed an expansive computational learning goals framework, where they analyzed teacher-articulated learning goals to point out the importance to teachers of developing CT dispositions, as well as grit, resilience, and mindset. The idea is that helping students develop a positive affect towards computation can make computation more accessible, less intimidating, and overall more of a positive learning experience for students. Currently, teachers have no way of assessing the impact that their computational activities, and in turn the computational integration as a whole, is having on their students' dispositions. This study lays the groundwork for building an assessment that evaluates students' dispositions in computation-integrated physics, but first, we need to understand how the Pérez framework applies to a high school physics context and what dispositions look like in these classrooms.

Thus, our primary research question is, **how do CT dispositions apply to the context of a computation-integrated high school physics class?**

Answering this research question entails taking the theoretical framework from Pérez [1] and applying it to a new context. The CT dispositions framework was developed in a mathematics setting through observing teachers and collecting the reflections of teachers. We intend to take the same framework and apply it to a physics setting through observing students and asking them about their perspectives. As this is a new context (computation-integrated physics) and new data sources (student perspectives), this will likely stretch the untested framework, which is part of the appeal of this study. By extending the CT dispositions framework to a new setting, we hope to strengthen it and make it more robust for other applications. If CT dispositions are as important as we argue here, then we anticipate the CT dispositions framework will build in usage and usefulness as it is applied to more contexts and used in curriculum development around computational activities.

Another consideration for our study is the relationship between CT dispositions and more established constructs that address students' attitudes and perceptions of computation. We turn to one such construct, mindset [2], because Pérez drew on it to develop the CT dispositions framework [1]. Additionally, mindset has been used in the past as a bellwether of performance in computational classroom settings [107, 108]. Because the CT dispositions framework is new in computation-integrated physics settings, we hope to tie our application of it to mindset. Mindset also varies based on context and method [2, 201], which provides further motivation to study both constructs in the same investigation.

With this in mind, our secondary research question is, **how are CT dispositions connected to mindset in the context of a computation-integrated high school physics class?**

We intend to answer this question by coding our data sources for dispositions and mindset simultaneously and using overlaps and patterns to point out aspects of the relationship between the constructs. We begin this endeavor in Section 7.3, where we outline the theoretical framework of CT dispositions, its connection to mindset through Pérez's work, and a framework for mindset that can be used alongside the CT dispositions framework. We proceed in Section 7.4 to outline our case study methodology for investigating dispositions and mindset. In Section 7.5 we describe the context of our case study and the features of one teacher's computational activities that make them an appropriate setting for CT dispositions to develop. In Section 7.6, we describe our methods, including participant selection, data generation, transcription, and data analysis. In Section 7.7, we show the results of our study. The first part of the results, Section 7.7.1, addresses the first research question and includes each student's dispositions profile, which puts together evidence from interview data and in-class recordings to make an argument for each student expressing a certain level of each CT disposition. The second part of the results, Section 7.7.2, addresses the second research question and shows evidence of different types of mindset that each student expressed, comparing it to the dispositional profile from Section 7.7.1. Finally, in Section 7.8, we discuss the results and their implications for future work in CT dispositions. We include recommendations for applying the framework and suggestions for potential changes to it for research studies where the participants are high school students in a computationally integrated physics class.

7.3 Theoretical Framework

Developed by Arnulfo Pérez [1], the CT Dispositions Framework is an attempt to operationalize the full definition of CT from ISTE and CSTA [132]. The ISTE and CSTA definition is split into two categories: practices of CT and dispositions of CT. Due to the broad research and attention that has been placed on CT practices to date [40, 133, 66, 196, 197] and the lack of focus on dispositions (only *recommendations* to take dispositions and perspectives into account [198, 70, 199]), Pérez developed a framework for researchers and teachers to use to understands how CT dispositions can show up in the classroom.

The framework was originally developed in the context of a workshop series for K-12 teachers where they learned how to integrate CT into their mathematics curricula. Pérez and other institute facilitators made observations of the teachers as they worked on CT activities, and they collected reflections from the teachers about their learning. Using the observations, reflections, and a synthesis of relevant literature, Pérez wrote the CT Dispositions Framework [1]. One of the key features of the framework development was the acknowledgment that it needs to be applied to other contexts: "the usability of the framework [increases] through examples of classroom behaviors that may accompany developing or higher levels of a given disposition" (page 442) [1].

The wording of "developing or higher levels" refers to the degree with which a person is disposed to willingly participate in opportunities that will increase their engagement with CT practices. For example, one of the dispositions in the framework is persistence. Having a high level of persistence is crucial for learning in CT activities as it means that when faced with a challenge in the computational activity, a student will continue to engage with it and as a result are more likely to engage in CT practices. Whereas, having a developing level of persistence can pose a barrier to learning as it can result in premature disengagement from the activity. That said, a developing disposition is, by definition, ripe for improvement and can be indicative of a student actually in the process of undergoing that improvement. Granted, the categories of "high dispositions" and "developing dispositions" are not strict categories; instead, we view "high" and "developing" as two ends of a continuous spectrum. In this way, the CT dispositions framework can be used as a tool for identifying how students align with the dispositions spectrum and can allow teachers to support growth in different areas of computational thinking dispositions.

In the CT dispositions framework, there are three dispositions identified by Pérez: tolerance for ambiguity, persistence, and willingness to collaborate with others. Their definitions and characteristics are listed in Table 7.1, which are synthesized directly from Pérez [1]. The characteristics of each disposition are categorized into key inclination, sensitivities, and abilities, which were adapted by Pérez [1] from Perkins et al [202]. The categories work together when a person acts out a particular disposition: "Inclination refers to an individual's tendency toward a particular way of thinking or acting. Sensitivity denotes an individual's attentiveness to opportunities to engage in that particular thought or action. Ability refers to being able to actually produce that thought or action when one notices an opportunity (sensitivity) and feels drawn to act (inclination).” (pages 434-435) [1].

The way the key inclinations, sensitivities, and abilities are tied to behavior and thinking make them ideal for observing through group work and reflective assignments, which is exactly how Pérez observed them at the original workshop series for teachers. This observable quality also makes these categories ideal for our study, which is why we use Table 7.1 as an analytic tool later in the paper. The degree to which a student displays inclinations, sensitivities, and abilities for a particular disposition is the degree to which that student *has* that disposition.

To be clear, the qualities described in Table 7.1 align with high dispositions, not the developing side of the spectrum. When using this framework later in the study, we interpret the qualities of developing dispositions to be opposite from the descriptions in Table 7.1. For example, the opposite of an interest in exploring unfamiliar situations (high) could be characterized as an apathy towards unfamiliar situations or an avoidance of unfamiliar situations (developing). We also acknowledge that although the framework accounts for developing and high dispositions, people can exist anywhere on the spectrum between developing and high. Even in the same excerpt, for example, a student may exhibit a high tolerance for ambiguity by expressing a desire to discover new meaning while exhibiting a developing tolerance by insisting there can only be one solution.

However, teacher observations were not the only criteria by which Pérez [1] developed the framework for CT dispositions. He also conducted an extensive review of literature on which to base his framework. Several times when describing the features of CT dispositions, he cited work on growth and fixed mindset [2, 5] or work foundational to mindset theory [203]. Pérez cites Dweck [2] when discussing “the malleability and potential growth of positive dispositions,” and again he cites her when he says, “tolerance for ambiguity...is malleable” and “all are capable of becoming increasingly tolerant of ambiguity, a form of growth” [1]. This suggests that Pérez connects the malleability of intelligence and skill (from mindset theory) to the malleability of dispositions, especially tolerance for ambiguity.

	Key Inclinations	Key Sensitivities	Key Abilities
Tolerance for Ambiguity: A tendency to experience ambiguous situations or stimuli as enriching and engaging	**1.** An interest in exploring unfamiliar situations **2.** The desire to discover meaning or possibilities that are not yet apparent **3.** A tendency to avoid rigid categories and take a flexible view of categorization **4.** An accepting view of variance	**1.** Awareness that engaging with uncertain situations can lead to growth **2.** Alertness to opportunities to clarify what is known and unknown **3.** Responsiveness to approaches for reframing ambiguous situations or stimuli	**1.** Acknowledging multiple possible solutions or explanations **2.** Finding value in undertaking "messy" tasks **3.** Navigating incomplete data and uncertain trajectories toward a solution
Persistence: A tendency to continue working or to maintain effort when dealing with a challenging task	**1.** The tendency to value extended effort **2.** The desire to complete difficult tasks **3.** An interest in what may be discovered even in an attempt that is not successful	**1.** Alertness to the characteristics of a given task **2.** Awareness of the satisfaction that will be felt when efforts eventually yield fruit **3.** Attentiveness to opportunities to shift tactics when needed	**1.** Sticking with a task for an extended period of time **2.** Trying a new approach after considerable effort **3.** Pursuing resources that increase the effectiveness of effort **4.** Framing significant effort as likely to produce significant outcomes
Willingness to Collaborate with Others: A tendency to coordinate effort and negotiate meaning with peers to accomplish a shared goal	**1.** A willingness to have one's course changed by interactions with others **2.** A tendency to invite and value perspectives different from one's own **3.** Curiosity about multiple possible approaches to solving a problem	**1.** Alertness to interpersonal dynamics that may enhance or impede effective interactions **2.** Responsiveness to the contributions of peers **3.** Attentiveness to the unique insights that emerge from interactions	**1.** Listening to and having one's actions shaped by others **2.** Articulating or justifying the benefits of a particular approach **3.** Clarifying, questioning, or negotiating the group's understanding and/or course of action

Table 7.1: Definitions, Inclinations, Sensitivities, and Abilities for each CT disposition. Features of the table are copied from different parts of Pérez [1]. The inclinations, sensitivities, and abilities as described here align with "high" dispositions.

Pérez also refers to mindset when discussing persistence, saying tasks that rely on rehearsed procedure "can reinforce the belief that success in mathematics amounts to completing problems quickly and easily" [1] He cites Yeager and Dweck [5], an article that connected resilience to growth mindset in mathematics contexts. This suggests that an activity designed around a rehearsed procedure that doesn't require deep thinking can reduce persistence (and can foster a fixed mindset, according to Yeager and Dweck [5]). Pérez clarifies this point, saying, "if students do not believe that their efforts matter in a particular context, they are unlikely to persist" [1].Again he cites Dweck [203], which demonstrates how teaching children to take responsibility for failure and attribute failure to lack of effort can help children improve their persistence. This is a direct connection between aspects of growth mindset (responsibility for failure and responding to failure with increased effort) and one of the CT dispositions (persistence).

Pérez did not draw explicit connections between mindset and willingness to collaborate, though he did for the other two dispositions and for dispositions as a collective. We find the use of mindset compelling because it ties the dispositions framework to a well-established [204] social cognitive theory often applied in educational contexts [204, 205]. There are several proven interventions [124, 125, 126, 127, 128] that can help foster growth mindsets among students, and drawing the connection to CT dispositions could mean that these same interventions might impact CT dispositions as well.

In deciding how to operationalize mindset for our investigation, we turn to Dweck's original theory [2], to a subsequent study where she and colleagues turned mindset into a questionnaire with explicit categories [4], to a later book by Dweck where she addresses the in more depth the behavioral patterns that give rise to growth and fixed mindset [3], and to a study that that connected resilience to growth mindset for adolescents in mathematics contexts [5]. We draw from these sources in the following descriptions and in Table 7.2. The foundation of mindset lies in two theories of intelligence that students may hold [4, 2, 3]. The first is called "entity theory," or more commonly, fixed mindset. This is the idea that intelligence is a fixed entity that is bestowed upon someone, and it cannot be changed by effort. The second is "incremental theory," or more commonly, growth mindset. This is the idea that intelligence is incremental, or changeable, especially when effort is applied to it. Dweck [2] argued that for students, a fixed mindset can be detrimental to learning because it leads to a loss of motivation in the face of adversity and harsher judgment of self when making mistakes. Conversely, students with a growth mindset respond to failures with increased effort and motivation to learn from the mistake.

There were several other aspects of mindset that we summarized in Table 7.2. Students with a growth mindset tend to have a desire to learn, whereas students with a fixed mindset wish to prove they are smart and/or superior [4]. Students with a growth mindset believe that thinking hard and making mistakes are worth it because they can help you learn, whereas students with a fixed mindset believe that thinking hard and making mistakes should be avoided because they show a lack of ability [2]. Students with a growth mindset believe that effort is valuable and the path to success, whereas students with a fixed mindset believe effort is not valuable, and too much effort is a sign of inability (i.e., successful students shouldn't have to try) [2, 4, 5]. Depending on the mindset, failure can have different implications [2, 4]. For growth mindset, failure means you need to study harder and/or better, whereas for fixed mindset, it means you are stupid, you are bad at the subject area (physics or computation in our context), or the assessment itself is unfair. Failure also holds different opportunities for the different mindsets [2, 4]. For growth mindset, failure is a learning opportunity, whereas for fixed mindset, failure leads to losing interest in the topic. Students with a growth mindset experience setbacks as roadblocks to overcome, whereas students with a fixed mindset experience setbacks as paralyzing their progress on an activity [4]. Students with a growth mindset take responsibility for their successes and failures, whereas students with a fixed mindset tend to attribute success and failure to external factors [4]. Mindset also splits along the value of trying different strategies or getting outside help when stuck: students with a growth mindset value these tools, whereas students with a fixed mindset do not [5]. Lastly, students with a growth mindset embrace challenges, whereas students with a fixed mindset avoid them [3].

Though we categorize mindset into "fixed" and "growth" columns in Table 7.2 and in our descriptions above, we also acknowledge that mindset can exist on a spectrum between the two columns. Students can exhibit different levels of growth or fixed mindset at different times, for

Growth Mindset	Fixed Mindset
Intelligence/skill is growable	Intelligence/skill is fixed
Learning is important	Proving smarts/superiority is important
It is better to learn even if you have to think hard or make mistakes	It is better to avoid thinking too hard or making mistakes
Effort is valuable because it makes you smarter and/or more skilled	Effort is not valuable because putting in too much effort means you aren't very smart, and it won't make you smarter
Failure can mean: you need to study harder, you need to study in a better way	Failure can mean: you are stupid, you are bad at physics/computation, assessment is unfair
Failure is a learning opportunity	Failure makes me less interested in physics/computation
Setbacks are opportunities to overcome a challenge	Setbacks are paralyzing
Success/failure is one's own responsibility	Success/failure is not one's own responsibility
Getting outside help and trying different strategies are valuable tools	Different strategies and outside help aren't valuable
Challenges are to be embraced	Challenges are to be avoided

Table 7.2: Indicators of growth and fixed mindset, developed from Dweck [2, 3], Blackwell et al [4], and Yeager and Dweck [5].

different subject areas, and for different aspects of mindset [2, 3, 4]. For example, a student might articulate that they believe effort is the path to success (growth mindset), but they also have a strong desire to prove they are smarter than other students (fixed mindset). They also may sometimes feel motivated to overcome setbacks and at other times feel paralyzed and unable to continue working after facing a setback (growth AND fixed mindset).

We expect for nuances like these to appear in our data, because nobody is a perfect exhibition of growth or fixed mindset (or any of the dispositions, for that matter). Additionally, mindset can appear differently depending on context and circumstances [2, 201]. We supply the categorizations in Table 7.9 simply as a tool to discuss the different aspects of mindset as they appear in the data. The same is true for the descriptions of the dispositions in Table 7.1—no student will encapsulate every inclination, sensitivity, and ability of a disposition. Those categories are simply there to help us show how a student reflects certain ASPECTS of dispositions in the data.

7.4 Methodology

Our methodology is case study, with the purpose being to see how the dispositions theory extends to students in a high school, computation-integrated physics classroom. We expect for some parts of the theory to align with the behavior of our participants given the original context of the theory and other parts to require rethinking for our setting. Case studies do not provide causal or correlative results nor can they be generalized to a broad audience. Case studies are for studying interactions within a phenomenon [46], and it is through studying human interactions between that we intend to illuminate the application and utility of the dispositions theory.

To clarify, a case study comprises a phenomenon and a case, around which the research is designed. Our phenomenon is the presence and manifestation of CT dispositions, and our case is a collection of students in a single high school physics class taught by Mr. Buford (pseudonym). Together, these form our main research question: What are the CT dispositions of students in Mr. Buford's class?

When we think about HOW we intend to pursue this research question, we employ aspects of two different traditions of case study: realist [47] and interpretivist [50]. A realist case study is characterized by several factors: the presence of propositions upon which the research is designed and the results are validated, "logic models" [47] that describe how claims will be constructed from data, embedded units of analysis (or multiple grain-sizes at which data is generated and analyzed), and comparison between cases. In contrast, interpretivist case study is characterized by the centrality of human interpretation in the data generation, the use of participant's viewpoints (called "anchor points" [50]) in the data to understand the "interpreted" phenomenon, and the focus on a single case (as opposed to comparing multiple cases).

The perspective we take on our case study lies in the overlap between the realist and interpretivist views. Both traditions attempt to "bound" the case in order to focus data generation on a handful of in-depth data sources. We do this by focusing primarily on interview data and in-class recordings of Mr. Buford's students. There are also aspects of each tradition that can coexist—we use propositions (e.g., high school students have CT dispositions that can be inferred from their behavior in physics class), we loosely use a logic model (described in methods section), we use embedded units of analysis (described below), we center human interpretation in our data generation, and we use anchor points (described below). Where the traditions contrast (comparison of cases versus a single case), we take a middle ground—we compare the findings between data sources as part of our discussion to see HOW the theory applies, but we don't compare cases, instead favoring the in-depth look at our single case of embedded units.

Our case (the students in Mr. Buford's class) is split in our research design into smaller embedded units of analysis. In this case, the embedded units are the individual students. We organize our findings based on these units in order to present how each student has their own set of CT dispositions. However, we do not keep these units separate—they serve the collective purpose of testing the theory of CT dispositions and connecting that to mindset theory as a well-established learning construct. By looking at the case as a whole (the collection of students), we also return to the phenomena of interest, which are how CT dispositions apply to a new classroom setting and how mindset is connected to CT dispositions in this context. As a parallel, we also view these students as “anchor points” when analyzing the data associated with them. In this sense, the students each provide a different instance of CT dispositions, and all together they provide us with a triangulated understanding of how CT dispositions manifest in a classroom.

In the methods section, we will describe in detail how we use our data sources to construct claims around CT dispositions and mindset (sometimes referred to as our “logic model” [47]). We also will describe how we link data to propositions and lay out our criteria for interpreting findings. For the methodology section, it suffices to articulate our propositions. Propositions are ideas for how the relationships of interest within our phenomenon come about [47]. We have two, formulated with respect to our two research questions. First, we propose that CT dispositions are present in what students say and do. Second, we propose that context-based connections between CT dispositions and mindset can be argued when both constructs describe the same piece of data. The first proposition helps mainly with data generation and analysis of dispositions. The second proposition helps mainly with analysis of the connection between dispositions and mindset.

7.5 Context

In this section, we describe Mr. Buford’s class as the context for our case study. Mr. Buford teaches physics at Mulberry High School (pseudonym), a suburban, affluent, racially diverse public high school, where he has been teaching for 30 years. The course we studied was a section of AP Physics 2. Initially, Mr. Buford integrated computation into AP Physics 1 in Spring 2018. After attending a summer workshop at Michigan State University for high school physics teachers who wanted to integrate computation into their physics curriculum, he then fully integrated computation into AP Physics 2 for the 2018-19 academic year. The 2018-19 academic year is when this study took place. For a detailed description of how Mr. Buford chose to integrate computation in his class and the process behind his curriculum design, see Chapter 6. In this paper, we focus on the features of Mr. Buford’s implementation that promote or provide opportunities for demonstrating

CT dispositions.

First, Mr. Buford's computational activities contain ambiguity in several forms. The computational activities were designed in the form of a minimally working program [186] using the GlowScript language [185], which means that Mr. Buford would provide students with the beginning of a program that would fully compile without presenting errors. However, the minimally working program is missing lines of code to properly model the physical phenomenon, which students are expected to fill in. At the start of class on a computation day, Mr. Buford would explain the minimally working program to the students. He would outline the physics concepts that they were supposed to model, which was always a concept the students had seen before either in a demo or drawn out on paper. While he explained the final output and the initial code, Mr. Buford did not provide steps or instructions on how to complete the code. This made it so there were multiple solution paths, and the students had the freedom to add whatever they wanted to, in any order they saw fit. In addition, even though the end result was typically the same visual for all the students, there were always several configurations of code that would produce the results students were aiming for. Furthermore, often students would need to look up functions or objects in the GlowScript library, which meant they would sometimes search online for ways to implement their ideas. This open-ended searching, together with the multiple solution paths and solution configurations, indicated several opportunities for students to demonstrate a tolerance for ambiguity during the computational activities.

The activities also afforded opportunities for students to exhibit and develop persistence. For example, Mr. Buford would design checkpoints throughout the activity. These checkpoints weren't explicit milestones for the students; instead, they were measures of progress that Mr. Buford used to check in with his students. In one activity, students were asked to model a ray of light using small spheres to represent the photons in that ray of light. The minimally working program for this activity provided a single, stationary ball and a rectangle that represented the lens. Mr. Buford expected the checkpoints of this activity to be: causing a single light particle (sphere) to move on the screen, and then make the light particle pass through the lens, and then change the angle of the

Figure 7.1: Mr. Buford's classroom setup. This snapshot shows students gathered around tables in groups of around three or four.

particle's path to correctly represent refraction through the lens, and finally to add more particles to the animation. These checkpoints highlight the difficulty of the task and students' need for persistence. There were several steps a student had to get through in order to complete the activity, and they were only going to succeed if they were willing to put effort into each step. Additionally, the students had most of the class period (45-55 minutes) to work on the activity, which meant there was an extended period of time over which they could work through the challenges of the computational activity.

Finally, collaboration is inherent in Mr. Buford's computational activities. First, the classroom is arranged into tables surrounded by four to six chairs each, which meant students sat facing each other, as shown in Figure 7.1. Additionally, the surfaces of the tables were whiteboards, which meant work done on the whiteboard could be seen by other students at the table. The only non-collaborative aspect of the activity was that students worked on their own code on their own laptops. However, Mr. Buford encouraged the students to work together and share ideas throughout the class period. Collaboration was not required for success like tolerance for ambiguity and persistence were, but it was encouraged by Mr. Buford's messaging and the design of the classroom. Additionally, the design of the activities made them challenging and ambiguous, making it easier to get stuck. This can translate into opportunities for students to ask one another for help and work together on the activity.

Thus, we expect students to express CT dispositions when working through Mr. Buford's computational activities because the activities are designed with ambiguity, persistence, and collaboration in mind. This is important because we need to have ambiguous stimuli and opportunities for exploration so that students can exhibit a tolerance for ambiguity. It is important for students to encounter challenges and have an extended period of time to engage with those challenges in order for students to exhibit persistence. We also need to have opportunities for dynamic interaction and negotiation in order for students to exhibit collaboration. Even the student on the highest ends of every disposition will not be able to express those dispositions in an activity that constrains them to work procedurally, without challenges, and alone. Given the design of Mr. Buford's activities, his classroom provides an ideal context to look for CT dispositions.

7.6 Methods

We selected students to include in our study based on the availability of data from an Chapter 6 meant to explore the landscape of student experiences in Mr. Buford's class. As stated in the earlier study, "participants were selected to represent a broad range of student prior experiences (in terms of physics classes and computational exposure) and current in-class experience (determined through in-class observations)." From these participants, we included the students for whom there existed interview data and in-class recordings from the initial data collection: Otto, Blaine, Ed, and Beck (pseudonyms). For our study design, it was important to have access to both data sources for each student because we are testing the theory of CT dispositions. We wanted to be able to capture student experiences from multiple types of data sources because the best way to identify CT dispositions is not well established. All four students were juniors at Mulberry High School at the time of data generation. To ensure we respected how the students wished to be represented in this study [187, 188], we asked the students after data generation to self-describe their gender identity, racial identity, and preferred pseudonym.

Otto took "regular" Physics 1 with a different teacher (Mrs. Carrera) before enrolling in AP Physics 2 with Mr. Buford. He usually sat at a table with the one other student (Blaine) who also jumped straight from Physics 1 with Mrs. Carrera to AP Physics 2 with Mr. Buford. Otto often had difficulties doing the computational activities because of his unfamiliarity with GlowScript. He tended to consult Beck, who sat at the neighboring table, for help during the computational activities. Otto self-identified as a white man.

Blaine took the same path through "regular" Physics 1 as Otto did. Blaine consistently had difficulties getting started on the computational activities. After a few minutes of trying unsuccessfully to make progress on the computation, he usually shifted his attention to joking around and spent minutes at a time stringing together jokes and lighthearted observational commentary to whoever would listen. Sometimes, if no one would engage with Blaine's banter, he directed it at Otto, even when Otto wanted to work on the activity at hand. Blaine self-identified as a cisgender biracial (Black and white) man.

Ed took AP Physics 1 with Mr. Buford the year before. She usually worked in a large group with three to five other students, including Beck. During class when she was working, she often talked out loud to herself and asked questions to herself. She felt a strong sense of community in the class, and she often checked in with her group mates to see how they were doing. Ed self-identified as a Black agender person. She clarified that she goes by she/they pronouns and suggested for us to pick one to use or alternate between she and they, with no preference among those options. We opted to use she/her pronouns alone for consistency.

Beck also took AP Physics 1 with Mr. Buford the year before. He worked in the same large group as Ed, which was usually formed at the start of class with students dragging three tables together. Beck was an avid coder, and he decided to learn more GlowScript and do Khan academy physics [206] over the summer after taking AP Physics 1. His dad was a computer scientist. Beck was often a resource for other students because he could finish most or all of a computational activity without help, and he liked to share his code and explain his thinking to other students. Beck self-identified as a white cisgender man. We placed Beck's portion of our results into Appendix A for the sake of brevity—the results section is already quite lengthy, and Beck did not provide many new insights in comparison with the other students in this study. Where appropriate, we describe and discuss the data from Beck and the meaning we interpreted from it, with a detailed analysis provided in Appendix A.

Our methods were guided by a set of propositions [47, 52]. These serve to motivate the data generation, transcription, and analysis that follow. First, we propose that CT dispositions are present in what students say and do. This motivates us to collect and analyze interview data and in-class recordings of students working, as well as construct a profile of CT dispositions for each participant in our study. Second, we propose that context-based connections between CT dispositions and mindset can be argued when both constructs describe the same piece of data. This motivates us to analyze our data for both constructs and present a discussion on their potential overlap in the data. Both of the propositions come from the development and use of the theories of the CT dispositions [1] and mindset [2]. It is with these propositions that we flesh out our methods below.

7.6.1 Data Generation and Transcription

We developed interview protocols and conducted semi-structured interviews [45] with the above four students. The interview questions were written to explore the students' feelings about physics class and computational activities in accordance with an exploratory research design that investigated dispositions. We also interviewed Mr. Buford and took observational field notes [207], which aided in writing the context in the previous section. Additionally, we recorded two of the student groups completing one of the computational activities in Mr. Buford's class. In this study, we focused our analysis on both the student interviews and the in-class recordings in order to construct a triangulated understanding of each student's CT dispositions. The choice to focus both on interviews and in-class data align with our first proposition.

Data Sources	
Student interviews	Four interviews
Teacher interview	One interview
Field notes	Six class periods
Classroom recordings	Two group recordings during one class period, capturing all participants

Table 7.3: Data sources used in this study (more were generated, detailed in Chapter 6).

The interviews were transcribed for utterances alone without non-verbal communication. This choice was driven by a focus on what participants say about their experience. The interviews were conducted to ask about the perspectives of the research participants, so their comments during the interviews are taken to represent this perspective. We understand that interview comments can only *represent* how someone feels about their experiences [189], but rather than try to capture every piece of information by analyzing non-verbal communication, we focus on what the participants say because their responses were prompted verbally. We only included non-verbal communication in the interview transcripts when it added meaning on its own to what a student said, such as a head-slap or eyeroll.

On the other hand, for the in-class recordings, we wanted to highlight non-verbal communication, such as gaze, gesture, and body position, because a student is much more likely to communicate non-verbally in significant ways when they are not being guided by interview prompts. We represent non-verbal communication with double parentheses. We also use special symbols for intonation, cadence, emphasis, and other speech patterns, drawing from Jefferson [6]. We provide a legend for the in-class transcription in Table 7.4.

7.6.2 Data Analysis

We used our two propositions to guide our data analysis and our interpretation of our findings. For the first part of our analysis, we coded the interviews and in-class recordings for CT dispositions,

Transcription Key	
:	Prolongs the sound immediately preceding, more colons for a longer prolongation (about 0.5 seconds for each colon)
(1.0)	Indicates time elapsed in seconds
word	Indicates emphasis
°word°	Encloses quieter speech
WORD	Indicates louder speech
?!,.	Indicates the usual intonation or continuation of speech (in-class and interview transcripts)
(inaudible)	Indicates an utterance that I couldn't make out
ˆwordˆ	Encloses speech spoken with the cadence of reading out loud
[	Indicates the simultaneous start of overlapping utterances
]	Indicates the simultaneous end of overlapping utterances
((word))	Encloses descriptions of non-verbal actions (in-class and interview transcripts)
$word$	Encloses speech uttered while suppressing laughter
word	Encloses speech with a creaky quality as if feigning being on the verge of tears
word-	Indicates where speech has been cut off
word<	Indicates the end of an utterance that came to an abrupt stop
word=	Indicates no elapsed time between equals signs
word	Bold text is used only for the write-up to draw the reader's attention (in-class and interview transcripts)
Int	Abbreviation for Interviewer (interview transcripts)

Table 7.4: Transcription Key. Some transcription symbols borrowed from Jefferson [6]. Symbols are used only for in-class transcripts unless otherwise specified.

using the inclinations, sensitivities, and abilities from the theoretical framework as a coding scheme. The results are provided in Table 7.4. This coding was motivated as a way of exploring our first proposition: CT dispositions are present in what students say and do. Using the results from our coding, we created a profile of CT dispositions for each student based on the overall patterns in the coding. We provide the patterns and examples of coding in the results section. This serves the purpose of demonstrating how the dispositions framework can be extended to a setting different from its original context.

For transparency, we often coded excerpts or utterances for CT dispositions, even when the excerpt was nothing about computation. This is because CT dispositions are more general than the subject of computation. For example, one can exhibit a tolerance for ambiguity in a variety of situations, and this builds into CT dispositions regardless of whether those situations involved computation. We still focused much of the data generation on computation-related interview prompts and computational tasks in class, but *everything* that students said and did mattered to us in cataloguing their CT dispositions.

For each data source, we examined utterances one at a time, or as a small set of utterances if a student stayed on the same topic. Each time, we checked to see if any of the inclinations, sensitivities, or abilities would describe what the student was saying or doing. To show this process, we include two examples of high and developing tolerance for ambiguity and how we coded them. As an example of the high tolerance for ambiguity code, Otto spoke out loud during class about what he knew and didn't know about the task at hand: "I know, its velocity, is gonna have to stay the same. But I don't know how to change that into like, an x and y, like separate components." He noted the velocity was constant but contrasted that with his uncertainty about how to split it into components. This recognition of what he knew and what he lacked lined up with a key sensitivity for tolerating ambiguity: alertness to opportunities to clarify what is known and unknown. The key sensitivity described what Otto said, so we coded this for a high tolerance for ambiguity, or more specifically, a high sensitivity for alertness to opportunities to clarify what is known and unknown. In contrast, Blaine provides an example of the developing tolerance for ambiguity code. Blaine described how he tried to get an answer that mimicked the teacher's in the interview setting: "I just do stuff until I can get an answer similar to his." He revealed a tendency to try and put together a solution that appears correct by the standards of the teacher's solution. In saying this, Blaine indicated an adherence to one type of solution, which *opposes* a key ability for tolerating ambiguity: acknowledging multiple possible solutions or explanations. The key ability *opposed* what Blaine said, so we coded this for a developing tolerance for ambiguity, or more specifically, a developing ability for acknowledging multiple possible solutions or explanations.

Though the examples above show single instances of an inclination, sensitivity, ability, or respective opposite, there were also utterances or excerpts to which we assigned multiple codes. Every coding choice depended on how we interpreted what a student said. Depending on how students described their experiences or feelings, we sometimes even coded a high aspect of a disposition right after a developing aspect of a disposition (a few times, the same disposition!), with both codes captured in the same excerpt of student talk or behavior. This mix of codes is represented in our results section, and we show the accumulated tallies in Tables 7.5-7.8.

For the second part of our data analysis, we coded the data sources for mindset, using our synthesis of mindset literature provided in Table 7.2. We did this coding to explore our second proposition: context-based connections between CT dispositions and mindset can be argued when both constructs describe the same piece of data. We framed this part of the analysis to see how CT dispositions compared with mindset codes. We discuss this comparison to help researchers and teachers connect dispositions to a more well-established construct, as well as evaluate Pérez's characterization of dispositions using mindset [1].

We note that in Table 7.2, we provided descriptions of both the growth and fixed codes, which is a contrast with Table 7.1, in which we provided *only* high (no developing) dispositions codes. This leads to a nuance with our mindset framework in that fixed mindset does not always equate to the opposite of growth mindset, and vice versa. For example, in the second row of Table 7.2, someone with a growth mindset values learning as important, whereas someone with a fixed mindset values smarts/superiority. These are not opposites. *Not valuing* learning (the opposite of the growth mindset statement) is not the same as *valuing* smarts/superiority. In analyzing for these codes in our data, we coded only for instances of fixed mindset and growth mindset, as opposed to opposite-of-growth mindset and opposite-of-fixed mindset, directly looking for statements that lined up with either column of Table 7.2. As an example, Blaine made a comment in class which got brought up in his interview: "what's the point of learning code? I can draw this on a piece of paper in fifteen seconds." This is an example where it is tempting to code this quote for Blaine's clear desire to *not* learn computation, a direct contrast to the growth mindset code, "learning is important." However, this statement was not coded. Instead, we coded a comment that Blaine made later in the same excerpt: "Just have a line, make it curve. I can do that, real quick...I don't need to plug it into a computer to draw some straight lines." In explaining his thinking, Blaine revealed a desire to avoid the challenge of plugging what he knew into the computer. This avoidance of challenges is a direct fixed mindset code, so we were able to analyze the excerpt and describe how certain features of it aligned with fixed mindset.

We interpret and evaluate our findings on a couple criteria (our "logic model"). First, we intend to see how well the dispositions framework described what students seemed to say and do, which would indicate the degree to which the first proposition describes our case. Second, we intend to ascertain the nature of the connection between mindset and dispositions. We have already outlined how Pérez connected the constructs [1] in our theoretical framework section, but we also dedicate part of our analysis to evaluating their connection in our data. Some relevant questions are: How is mindset reflected in dispositions in our data? How is it not reflected? How do these results compare to how Pérez connected mindset and dispositions in his theory of CT dispositions? Exploring these questions will indicate the degree to which the second proposition describes our case.

7.7 Results

We organize our results into two subsections. First, we construct a CT dispositions profile for each participating student. Second, we analyze that same data for mindset and show how the frameworks connect in the data. In this section, we first present the results of Otto, who demonstrates many of the high level dispositions and shows a growth mindset. Then, we discuss Blaine's results as a contrasting case; he demonstrates many of the developing dispositions and shows a fixed mindset toward computation-integrated physics. Finally, we present the case of Ed, who exhibits a mixed perspective on both dispositions and mindset, emphasizing the spectrum of possibilities with these constructs. We do not present Beck's results in detail here because he also showed many high-level dispositions and a growth mindset. Given the overlap between Otto and Beck's codes, we did not gain much additional insight into the framework from Beck's results, so we summarize his perspective at the end of the section and include Beck's full analysis in Appendix A for those interested.

7.7.1 Dispositions Results

For each student we provide a disposition profile, which uses data from their interview and in-class behavior to construct a picture of their CT dispositions as described in Table 7.1.

7.7.1.1 Otto Disposition Profile

Otto's statements and actions demonstrated high levels across all dispositions. In Table 7.5, we show all of Otto's codes from both the interviews and in-class data. The codes have been split between dispositions to show how his data may have revealed differences between his CT dispositions. In Otto's case, he had high levels across the dispositions. One aspect of Otto's table, which we will return to, is he had many more instance of tolerance for ambiguity in his interview than in his in-class data.

7.7.1.1.1 Ambiguity

From interview statements, Otto demonstrates a high tolerance for ambiguity. Below, he described his thought process when he works through a complex physics problem (non-computation).

Otto.Interview.1:

	Tolerance for Ambiguity	Persistence on Difficult Problems	Willingness to Collaborate with Others
Otto Interview	21 high 1 developing	11 high 1 developing	13 high 2 developing
Otto In-class	9 high 0 developing	9 high 0 developing	15 high 1 developing
Otto Total	**30 high** **1 developing**	**20 high** **1 developing**	**28 high** **3 developing**

Table 7.5: Coded instances of dispositions for Otto, separated by data source and tallied.

OTTO I just kind of look at what I have and then, I just- I think about it. I just try to go look at something and try to go off how that's related... I'll just try to go through the process of how things work, **see how- where different values appear**. Yes, if I'm looking at a sheet of equations, **whatever we already have**. And just try to find a way that makes sense for me in my head. Try to find **some solution that logically makes sense to me**.

His general approach is to survey what information or equations are available to him and see what he can find from there. His tendency to see "where different values appear" and look at equations "we already have" demonstrates an alertness for opportunities to clarify what is known about the problem. After clarifying, he describes trying to find a solution that makes sense, which aligns with the key ability to navigate incomplete data towards a solution.

In the computational activities, Otto demonstrated a similarly strong tolerance for ambiguity. For example, he chose to talk about the example of electrons in a magnetic field when discussing his approach to computational problems.

Otto.Interview.2:

INT What process do you go through when you have to do a GlowScript problem?

OTTO ...We were doing particles, like electrons moving through magnetic fields and how they move. See where the forces were and everything. I guess with that specifically, you just think about which direction things go and what kind of vectors and how strong they all are, I guess. **To break it up into each individual little piece and just figure out the order and everything that goes together.** How they're tied together.

His approach was to break down the information in the problem into vectors and figure out how it all went together. Specifically, he describes it as, "breaking it up into each individual little piece and just figuring out the order and everything that goes together." As indicated previously, Mr. Buford framed the computational problems as inherently ambiguous so this act of reorganizing and tying different pieces of the problem together is an approach for reframing an ambiguous situation. Otto did this to work towards a solution to the computational problem, which points to navigating through uncertainty towards a solution.

Otto was also aligned towards being curious and open towards computation when it was first introduced into the class. This was his response:

Otto.Interview.3:

INT Was this the first time you used Python?

OTTO Yeah. Yeah. He was just kind of like, 'We're doing coding today.' I was like, **'Oh, I guess I'll figure it out a little bit.'**

He was interested in figuring out the unfamiliar activity he was about to embark on. Otto could have easily had a negative reaction and decided that he would be unable to do the day's activity since he had no previous experience with GlowScript or Python. Instead, his reaction to learning about the new computation was, "Oh, I guess I'll figure it out a little bit." This willingness to figure out something he had never done before indicates an interest in exploring unfamiliar situations.

In class, most of what Otto displayed about his tolerance for ambiguity was when he talked about what he did and didn't know about the problem. For example, the excerpt below shows Otto talking about his options for specifying how a particle would move in his program. Leading up to this conversation, Otto was trying to tell Beck how he wanted to write the condition of his while loop. Otto was weighing the options of using the lens (represented by a "box" in the code) versus using the x-coordinate of a moving particle as it reaches the lens.

Otto.In-class.1 / Beck.In-class.6:

OTTO Yeah. And I don't really wanna use like the actual, [box

BECK [Now you just have to

OTTO **I don't wanna use the actual like lens as the thing that triggers it I just wanna use the coordinate as the thing that triggers it**

BECK Well yeah

OTTO But

BECK Whenever it's x posi- Once its x position reaches= the x position of the lens= which is zero, then you can make the change

OTTO =Zero =Yeah

Otto understands there can be multiple triggers in his program for the particle motion, and he indicates a preference for one solution path without implying that there is only one answer (only that he "wants" to use the coordinate). This indicates an acknowledgment of multiple possible solutions to this aspect of the problem.

Later during class when the researcher (Hamerski) was sitting at Otto's table, Otto started explaining unprompted where he was at in the problem. The "it" below refers to the moving light particle, whose path Otto is trying to refract through the lens in the code.

Otto.In-class.2:

OTTO I know, its **velocity, is gonna have to stay the same.** But I don't know **how to change that into like, an x and y, like separate components.** Gah:

Otto demonstrates that he can reiterate what he knows about the problem ("velocity is gonna have to stay the same") while identifying the parts that he isn't sure about yet ("how to change that into...separate components"). This awareness indicates alertness to an opportunity to clarify what he knows and doesn't know.

Overall, we saw evidence for Otto's high tolerance for ambiguity in both his interview and his in-class conduct. He demonstrated several of the key inclinations, sensitivities, and abilities: an interest in exploring unfamiliar situations, an alertness to opportunities to clarify what he knows, acknowledging multiple solutions, a responsiveness to approaches for reframing ambiguous situations, acknowledging multiple possible solutions, and navigating incomplete data and uncertainty to find a solution.

7.7.1.1.2 Persistence

Otto also demonstrates a high persistence on difficult problems; however, he once expressed in his interview a single indication of developing persistence for the computational activities when we asked Otto about how he feels upon completing the computational problems. His response indicated that he doesn't always feel satisfaction when he completes the activity, showing a developing sensitivity toward persistence. In the conversation before this excerpt, Otto was discussing how he often feels like he can't succeed at Mr. Buford's computational problems because he doesn't know the programming language very well.

Otto.Interview.4:

INT Is there a point when you get [the code] to work or is it just like class ends and you're still like, don't know what you're doing?

OTTO **I got it to work, eventually**, but it was still where it's like, **'finally'** type thing, not like, 'Okay, yeah.'

INT It wasn't. Okay. It wasn't like, satisfying or anything?

OTTO No, it was just kind of like, **'Yeah, I know it should've been working that entire time.'**

For the computational activity that is coming to Otto's mind at this moment, he "got it to work eventually," indicating that he stuck with the task for an extended period. However, he expresses some feelings of exhaustion, saying "finally," and "it should've been working that entire time." He says that he wasn't satisfied, despite the success that his efforts yielded. This demonstrates that Otto does not always articulate high persistence, even though he does supply a great deal of effort towards solving the computational problems.

In contrast to his interview statement, Otto displayed a high persistence during class. For example, he continuously ran into computational roadblocks during class and each time persisted by asking for help or diving back into the work to see where he could fix the issue. The excerpt below shows Otto asking for help. Leading up to this conversation, Otto was working consistently and just ran his code, which gave him an error message for an undefined variable.

Otto.In-class.3:

OTTO Ah, mm. Why is that wrong? Mm. **BECK. Why is it undefined?** [No. I've been doing-

BECK [°Yeah.° (inaudible). °It's pretty cool°

OTTO Um:. It said that x was undefined here for some reason. Like °I dunno what's wrong°. See?

BECK Um.

OTTO So: it says right here in line 17.

BECK ˆLine 17ˆ at or °(inaudible)° okay. Uhm.

(3.5)

BECK ˆVel dot position dotˆ Ok, well vel, you just need vel dot <u>x</u>, not vel dot position dot <u>x</u>, cause vel [is (inaudible)

OTTO [Oh:: (2.0) Thanks:

(7.0)

OTTO ((laughs uncontrollably)) $To be honest I don't [ra-$

BLAINE [No dude just ah- y- you got it.

OTTO That's a good step though.

(2.5)

OTTO ((lifts up laptop and turns it into camera's view)) **IT WENT UP, I NEEDED IT TO GO DOWN.** ((laughs quietly through nose, and then a hard exhale)) So I just need to switch<

(2.5)

OTTO (inaudible)

(9.0)

OTTO Oh, [because **it needs to be. (1.0) Negative. Ah: that's why**

His reaction was to call out for Beck and ask him why the variable is "undefined" as the error message seems to indicate. Otto's recognition of his need for Beck's help shows an attentiveness to the opportunity (presented by the error message) to shift tactics in order to move forward. Beck proceeds to attend to Otto and help him handle the error. After this, Otto runs into another problem related to the animation ("It went up, I needed it to go down"). He continues to expend effort by working on his own for the next few moments, eventually arriving at an explanation for the issue ("it needs to be negative, that's why"). Otto's perseverance through multiple roadblocks points to an ability to stick with the task for an extended period. He also demonstrated an ability to pursue a resource (Beck) who could help translate Otto's efforts into progress.

Later during the class period, Otto turned to Mr. Buford for help. When Otto was communicating what part he got stuck on, he reviewed all the steps he had taken so far.

Otto.In-class.4:

OTTO **((briefly raises hand)) Mr. Buford.** Okay. Okay.

TEACHER ((takes chair with one hand, lifts it up and moves it forward so he can stand to Otto's left and look at laptop screen))

OTTO So what I've got right here.

TEACHER Yeah. That works.

OTTO °Yeah°. But, **this is gonna- it's supposed to be the focal point.**

TEACHER Oh. [Alright, so, °ah°]

OTTO [So that's why, it's weird.]

TEACHER ((takes glasses out of shirt pocket and puts them on)) So how did you defi:ne. ((squats and folds arms on corner of table next to Otto)) How did you define which way it would go after it cot- got to the lens? [What did you say?

OTTO [Alright, so. **I took the speed, and I did a bunch of: trig stuff. So I found the angle right here. That it would need to go at. And I tried to turn that into a: like x: components and y components of a vector. And I just changed the velocity there.**

From the beginning of the interaction, we see Otto raising his hand and calling over the teacher to help: "Mr. Buford." The seeking of help at this point (with about eight minutes left in class)—after working at his program for most of the class period—indicates that Otto wants to continue working at the problem, a sign he has the ability to stick with a task for an extended period of time. As they begin interacting, Otto specifies the source of the issue for which he is trying to get help: "this is gonna- it's supposed to be the focal point." His awareness of where this issue comes into play, his knowledge of how it should be different, and his ability to point it out to Mr. Buford all indicate that he is alert to the characteristics of the task.

Overall, Otto had a disposition for high persistence on difficult problems, though he once indicated that the computational problems did not make him feel satisfied for his efforts. In terms of the key aspects of persistence, in the above excerpts Otto demonstrated an alertness to a task's characteristics, an attentiveness to opportunities to shift tactics when needed, an ability to sticking with a task for an extended period of time, and a pursuit of resources that increased the effectiveness of his effort. On the developing side, Otto also showed that was unaware or unable to experience satisfaction from the fruits that his efforts yielded.

7.7.1.1.3 Collaboration

Otto further demonstrated a high willingness to collaborate with others. According to Otto, this is something that is designed into the norms of the class:

Otto.Interview.5:

INT What about the people you sit near? Do they kind of expect you to need help during the coding or- ?

OTTO I wouldn't say they expect it, but they're not surprised when I do. See what I mean? **It's more of just an accepted thing that you help people.**

In his last utterance, Otto identifies a norm of in-class work: "It's more of just an accepted thing that you help people." Earlier in the interview, Otto indicated that he had taken up these norms, too. When he gets stuck, he turned to his peers for help before considering asking the teacher:

Otto.Interview.6:

INT That makes sense. What role does Mr. Buford play when you're working with your classmates?

OTTO Usually **most problems can be understood just by talking to other people** like Beck and those people that are good at it. But if you, nobody really gets it at all, you can just ask him and he'll come over and explain it and help walk you through the process of what's happening.

This quote demonstrates his willingness to ask for help, and it also demonstrates that he sees Beck's smartness as a benefit to him rather than a threat/competition. The connection Otto makes between understanding and collaborating ("most problems can be understood just by talking to other people") indicates a tendency to value different perspectives and an attentiveness to the insights that come from interactions.

Furthermore, Otto demonstrates his awareness of his peers and the value he puts on their explanations. Otto explained how he views the "smart" students, saying that the best indicator of smarts is the ability to explain concepts to peers.

Otto.Interview.7:

INT Is it like everybody's on equal footing, contributing the same thing?

OTTO It's pretty egalitarian, yeah. I feel like, at least I personally, tend to take more of an explainer type role. I think I have a little bit of aptitude for physics. Like the dude that sits behind me, Beck, he's probably like- **If you could say one person was an explainer type guy, it's him. He's really smart. Joyce too... She's really smart.**

INT It sounds like you're equating smartness with explaining.

OTTO Well, ability to explain. There's some people that are about as good as [Beck and Joyce] are in terms of just getting problems right and understanding the concepts. **But [Beck and Joyce] tend to be the ones who are able to express that to other people.**

Otto sets up a relationship between explaining well and being smart. He identifies Beck and Joyce as the top explainers and smartest students in the class: "If you could say one person was an explainer type guy, it's Beck. He's really smart. Joyce too...She's really smart." By recognizing the merits of explanation, Otto is demonstrating an alertness to an interpersonal dynamic (explanation) that enhances effective interactions.

In the above excerpt, Otto recognizes that having the ability to explain to others is a good thing. However, he doesn't always take this view. Later in the interview when talking about his strongest class, calculus, he admitted that he doesn't like to work together as much.

Otto.Interview.8:

INT Do you work in groups in [calculus] class or is it by yourself?

OTTO That one's a lot more solitary, I'd say. We get work time, but usually it's just trying to figure out the problem yourself.

INT Do you like that more?

OTTO Yeah. I'd say so. **Groups are fun, but I think I tend to work better by myself.** Especially in something like Calc where I feel like I have a **stronger base** and everything.

He admits that he prefers to work alone in calculus: "Groups are fun, but I think I tend to work better by myself." This indicates a resistance to having his course of action influenced by interactions with others. The justification he gives for his reservation is that he has a "stronger base" in calculus. Oddly, his extra strength in calculus may indicate that his peers have even more to gain from his help than they would in physics, yet he is more reluctant to collaborate.

From the in-class data, Otto seems to be highly disposed to collaborating with peers. Below, we analyze an example of Otto collaborating with Beck on implementing an animation for a moving light particle. In the lead-up to the excerpt, Otto asked Beck to help ("Beck help me") and invited Beck to provide his own perspective on how to edit the code ("How do I make it move?"). Below, their collaboration plays out after Beck has helped for a little while but there are still errors to deal with.

Otto.In-class.5 / Beck.In-class.3:

OTTO So run that and it'll just, ((pointing)) straight

BECK Let's see what happens, should do (inaudible). Straight to the right. ˆ**Inconsistent indentation one full**ˆ**-** let's see, see that's why I didn't- Alright so, light- I'm just gonna

OTTO Just retype it

BECK ˆ**While light dot position dot x less than**ˆ, °what was it?°

OTTO Light- I mean um

BECK Focal point?

OTTO **Uh, yeah. Focal point dot pos: x**

BECK °Position dot x°

OTTO Hundred

BECK °Velocity one hundred°

BECK Er::, oh! Got it. Oh, colon

OTTO Oh you need a colon? Ah!

BECK One hundred. Yeah, that's a thing you do need. **It should- Yeah! And that just travels straight to the right.** Until it gets to there

The sequence of contributions follows the pattern of Otto making a verbal contribution (e.g., "just retype it") and Beck reading or adding to the code (e.g., "while light dot position dot x less than"). The overall trajectory of the interaction moves from an initial error ("inconsistent indentation one full-") to an eventual solution ("It should- Yeah! And that just travels straight to the right"). Otto's utterances along the way point to his ability to clarify and negotiate the shared understanding and course of action. Otto didn't just hand his computer to Beck and say "fix it"—he's working together with Beck and suggesting paths (e.g., "just retype it"), contributing chunks of code (e.g., "focal point dot pos x"), and clarifying the known quantities (e.g., "hundred"). The eventual solution to Otto's coding problem represents Otto's willingness to let the interaction with Beck shape his course.

Overall, Otto displayed a disposition for high collaboration with others. This was clear throughout his interview and in-class behavior. He displayed several inclinations, sensitivities, and abilities aligned with high collaboration: a willingness to have his course changed by interactions with others, a tendency to invite and value perspectives different from his own, an attentiveness to the unique insights that emerge from interactions, an ability to listen to and have his actions shaped by others, and an ability to negotiate the group's understanding. The only exception was his hesitancy

	Tolerance for Ambiguity	Persistence on Difficult Problems	Willingness to Collaborate with Others
Blaine Interview	3 high 9 developing	2 high 7 developing	4 high 7 developing
Blaine In-class	0 high 12 developing	1 high 10 developing	3 high 3 developing
Blaine Total	**3 high** **21 developing**	**3 high** **17 developing**	**7 high** **10 developing**

Table 7.6: Coded instances of dispositions for Blaine, separated by data source and tallied.

to collaborate with peers in calculus class, which we return to in the discussion section. This particular excerpt was coded for an Unwillingness on Otto's part to have his course changed by interactions with others.

Through all the dispositions, Otto aligned with the high end of the spectrum. There were a couple exceptions, most notably the lack of satisfaction he feels after persisting through a computational activity and his tendency to prefer working without collaboration when he doesn't need help. However, the vast majority of Otto's data that we analyzed pointed to high dispositions for tolerating ambiguity, persisting, and collaborating.

7.7.1.2 Blaine Disposition Profile

In contrast to Otto, Blaine's statements and actions demonstrated dispositions that ranged from barely developing to somewhat developing. His coding results from both the in-class data and his interview are summarized in Table 7.6. There did not seem to be any major differences between the data sources for Blaine. The tallies for Blaine's collaboration suggest that he could be near the middle of the spectrum, but based on the content of his interview comments and in-class behavior, which we detail in Blaine's collaboration section a few pages below, he is actually more developing than this table indicates.

7.7.1.2.1 Ambiguity

Blaine presented a developing tolerance for ambiguity. He often made statements in his interview and in-class that showed he did not possess the key inclinations, sensitivities, and abilities associated with high tolerance for ambiguity. At times, Blaine expressed distaste towards a lack of clarity, or he refused to engage with complex problems. For example, he recalled a time when he had to create a magnetic motor as part of a physics project.

Blaine.Interview.1:

BLAINE We had a motor project where he just gave us a wire and a magnet and he was like, **'Do it.'**

INT Okay. Can you describe that for me?

BLAINE Well, he just gave us a wire and the magnet and he was like, 'Come back with a motor and explain how you did it.' **I waited until the last night.** I was rummaging through the kitchen cabinet trying to pull out some stuff. But it was really stressful because it was hard to get it to continuously work.

INT The motor?

BLAINE Yeah, the motor because I can get the- I think what he wanted was- **He didn't ever say what he wanted but you had to put the wire into a loop and then get it to keep spinning for twenty seconds.**

Blaine interpreted the teacher's statement of the project to be just "do it," indicating that Blaine found a lack of clarity around the assignment. In the last line, he again emphasized that Mr. Buford "didn't ever say what he wanted," yet Blaine also somehow had an understanding that he had to get the motor "spinning for twenty seconds." This discrepancy indicates that the actual uncertainty lied in HOW to get the wire spinning properly. He was focused on this open-ended request from the teacher, and only described the other features of the project when we asked for elaboration. These signs indicate that Blaine was not keen to navigate the incomplete data or the uncertain trajectory of the project.

At a later point in the interview, Blaine described his general approach to problem-solving in class:

Blaine.Interview.2:

BLAINE I'm just like, **'I'm going to take every equation on this equation sheet and we're going to see what I can make happen.'** He usually puts his answers at the front, so I just do stuff until I can get **an answer similar to his**.

When Blaine's not sure, he just takes "every equation on the equation sheet" and sees "what [he] can make happen." In contrast to Otto who used the equation sheet to identify values, connect with what was given in the problem, and to make sense of the problem, Blaine indicates going through "every equation on the equation sheet," testing them one by one. This simple approach indicates a lack of willingness to explore the unfamiliar situation and figure it out on a deeper level. He also accepts an answer "similar" to the teacher's, meaning Blaine is concerned with the appearance of correctness over conceptual understanding. He isn't interested in discovering meaning not yet apparent or even considering multiple possible solutions. Blaine cares primarily about having an answer that looks correct by superficial standards.

Given Blaine's avoidance of ambiguity, we asked in his interview if there was anything at all from the open-ended computational activities that he saw as beneficial. The question itself was quite leading, but it showed that Blaine can identify the benefits of ambiguity when asked.

Blaine.Interview.3:

INT Is there anything new that [computation] brings to the class: new material or new understanding, new ways to see the physics?

BLAINE I guess if you can actually do it, **it gives you visuals on what would actually happen.** Because most of them it's stuff we can't- an electron going into something and **we can't see that. It gives us real examples of what's going on.**

He acknowledged that there are some physics concepts you just can't see, like electron motion, and the code helps "give you visuals on what would actually happen." This was the only time he expressed an embrace of uncertainty related to computation or physics. When he acknowledges, "we can't see [an electron]. It gives us real examples of what's going on," Blaine is displaying an understanding that computation helps reframe the ambiguous physics concept to make it more accessible.

Despite his statement above, during the in-class work, Blaine often displayed a frequently negative stance towards ambiguity in the computational activity. Blaine demonstrated a frustration that the computation could not be more straightforward and literal. For example, when Otto articulated a roadblock he encountered in the code, Blaine became frustrated and defensive about the pattern of roadblocks that he encounters all the time:

Blaine.In-class.1:

OTTO I have like this velocity vector saying that it's going to the right, at that- but I don't know how to turn that into just a, you know. Down and to the right. Or up and to the right, or whatever

BLAINE ˆDown, parentheses ninety degrees.ˆ **<u>That's</u> how it should be. If I put in <u>line</u>, a line should appear.** I don't understand why it doesn't, you know?

Blaine was not willing to try to interpret how the code worked, he just expressed disapproval with how it did not obey his commands ("that's how it should be"). This indicates that Blaine has no desire to understand how computation works and by extension no desire to discover the meaning associated with the computational task. His input-output stance ("If I put in line, a line should appear") reveals that he has rigidly categorized the way he thinks GlowScript should work. This straightforward view also indicates no interest in navigating an uncertain trajectory toward a solution when dealing with computation.

Blaine again demonstrates an unwillingness to engage with uncertainty when faced with errors in his program. Instead of deciphering the error or reworking his program, Blaine searching online for sample code that he can simply copy-paste into his program.

Blaine.In-class.2:

BLAINE and then look. dude I did it look at how good I am. you see that? **error unexpected? what?** ((taps six times on mouse)) **I don't know how to code**

(4.0)

BLAINE ((while searching online)) ˆcode. for. l<. straight. line. in glow script. in glow s:cript. glow: s:cri:ptˆ

(8.0)

BLAINE **ˆSample code. Code glowscriptˆ**

(19.0)

BLAINE ˆGlowscript lightˆ (inaudible). ˆGlow. Glowscript. <u>Glow</u> script drake sample? Glowscriptˆ

The episode began with Blaine trying to run some code that he thought would work. He got an error ("error unexpected? what?"). His response to this surprise roadblock was to express, "I don't know how to code," which demonstrates that he was unable to see this as an opportunity to grow by engaging with an uncertain situation: the error message. He also searched the web for "sample code" that he could use in his program, a strategy that he returned to three minutes later after making no progress ("Sample code! ˆGlowscript. Glow:scriptˆ...I don't want a tutorial I just want sample code."), indicating that he was not interested in reframing the ambiguous situation that the error message presented.

Given the abundance of negative statements, it is clear that Blaine would rather search for easy answers than explore the problems on his own. He seems to recoil from situations that present uncertainty. Overall, Blaine was resistant to engaging with ambiguity, indicating a barely developing tolerance for ambiguity. When examining the key inclinations, sensitivities, and abilities present in the above excerpts, we saw that Blaine had no interest in exploring unfamiliar situations, no desire to discover meaning not yet apparent, a tendency to rigidly categorize, an unawareness that engaging with uncertain situations can lead to growth, an unawareness of opportunities for reframe ambiguous situations, an adherence to the idea that there is only one solution path, and an inability to navigate uncertain trajectories toward a solution. On one instance when reflecting on the big picture of computation in Blaine.Interview.3, Blaine displayed an appreciation for computational opportunities to reframe ambiguous situations, but this type of tolerance for ambiguity was rare. Given that the dispositions are framed as a spectrum rather than a categorization in the Pérez paper, Blaine would align near the lowest, developing end of tolerance for ambiguity.

7.7.1.2.2 Persistence

Blaine also sits close to the low end of the persistence spectrum since he displayed little evidence of persistence on both physics problems and computational problems. After describing the motor project in Blaine.Interview.1, Blaine went on to discuss other stressful and time-sensitive features of the project. Afterwards, we asked whether he might have learned anything:

Blaine.Interview.4:

INT Did you feel like you learned something when you did that?

BLAINE I learned that YouTube can teach you a lot of things.

INT It's a resource, is it?

BLAINE Yeah. It explained how the motors were working because we had to figure out how to get them to work and use the magnet to simulate the current and stuff. **It put some of the things we were learning in class and physically applied them to make sense of it.**

In the end, he feels like consulting YouTube helped him contextualize the concepts he had been learning about ("physically applied some of the things we were learning in class"). The way YouTube helped Blaine put the physics concept into action indicates that he pursued a resource (YouTube) that could increase the effectiveness of his efforts. This is one of only three codes for high persistence that we found from Blaine's data. Even though Blaine referred to YouTube as a reference, his use of YouTube could be framed as an easy way out of a difficult, in-depth project. This would make sense given Blaine's approach to "wait until the last night." Together, this could be classified as an inability to connect significant effort (putting time and effort into the project) with significant outcomes (completing the project), which makes this excerpt represent both high AND developing codes for persistence.

Despite occasional instances of high persistence codes, the vast majority of what Blaine says and does in the data illustrates a developing persistence on difficult problems. Below, Blaine describes how he avoids effort when presented with a computational problem.

Blaine.Interview.5:

BLAINE **I would try if I could literally get anything.** But since I literally can't get anything but a blank screen, I don't really try to do any more because **I'll put in a hundred things and then I'll just get a blank screen or I'll get some error.** It's like, 'Line 17.' Well, I don't know what line 17 is, man.

This demonstrates once again his lack of engagement in extended effort, this time for the computational activities. He indicates that he *would* try "a hundred things," only to "get a blank screen or some error," but we do not code this for high persistence because he indicated that he has given up on trying anymore ("I would try if I could literally get anything"). The sequence of error messages and blank screens after trying so many times shows that he was unable to change his approach after considerable effort. Even when thinking about what Blaine means when he says that he tried so many times, it helps to consult his in-class attempts at progress, such as the one in the next excerpt, which did not involve much action or overcoming of roadblocks.

During class, Blaine displayed further evidence of a stunted persistence. At one point in class, Blaine displays some relatively consistent engagement with the problem. He runs into an issue where he's not sure how to represent a variable as a vector in the code. He speaks to himself throughout the excerpt.

Blaine.In-class.3:

BLAINE How do you make position a vector?

(3.5)

BLAINE It says position °must be a vector°

(6.5)

BLAINE **((stands up to gaze over Beck's shoulder))**

(26.0)

BLAINE **I cede**

The error was new to him, but within ten seconds he decided to seek answers by looking at Beck's code. This may at first seem like an effort to leverage Beck as a resource, but Blaine does not interact with Beck as Otto did. Instead, Blaine opts to try absorbing or copying the answers by looking at Beck's code over his shoulder. Less than half a minute later, Blaine announces that he "cedes," or gives up, which demonstrates that he is unwilling to put much effort or time into the task. This demonstrates a devaluation of extended effort and an inability to stick with the task for much time. His disengagement with the activity continued for the rest of the class period, about ten minutes. Blaine's attempt at making progress was devoid of persistence, which helps characterize what it means to Blaine to try, as discussed in Blaine.Interview.5, the previous excerpt.

Blaine was quick to give up when encountering challenges in the computational activity. In terms of key aspects of persistence, Blaine exhibited no regard for the value of extended effort, an inability to stick with a task for an extended period, an inability to change approaches after considerable effort but no progress, and an inability to connect significant efforts with significant outcomes. On one occasion, in Blaine.Interview.4, he demonstrated an ability to pursue a resource (i.e., YouTube) that increased the effectiveness of his effort. The rareness of high persistence and the abundance of developing codes reflect a disposition for low, developing persistence.

7.7.1.2.3 Collaboration

Furthermore, Blaine also demonstrated a disposition for a developing willingness to collaborate with others. He tends to work solo, and when he does ask for help, the request is often transactional in nature, as if he is just looking for answers, not looking to develop a shared solution with meaningful contributions from multiple people. He describes his approach to in-class physics problems below:

Blaine.Interview.6:

BLAINE I just usually sit next to Otto. Then Otto will know most of the stuff. Then he'll ask Beck how to do other stuff and **I just watch what they're doing. I'm like, 'All right.' Then I try to do it** because if I were to ask questions for every problem I need help with, **I'd ask questions on every problem.** I just don't even really...I just try and figure out how they got there.

Blaine describes observing Otto and Beck and then trying to do the problem based on what he saw, rather than participating in the collaboration. This does technically represent an ability to listen to and have his actions shaped by others and an attentiveness to the insights derived from interactions, even if the interactions don't involve Blaine. However, his silent observation points to an inability to clarify, question, or negotiate the understanding that Otto and Beck are building. In fact, Blaine expresses a trepidation to ask questions, out of fear that he would "ask questions on every problem." This is an excerpt where Blaine exhibits both developing *and* high codes for collaboration.

In all, Blaine articulated a preference for working on his own and trying to replicate what he sees from other students than actually working together to co-create a solution that all parties can benefit from. Another indication of his developing willingness to collaborate is his unwillingness to ask the teacher for help:

Blaine.Interview.7:

INT Do you ever get Mr. Buford to help?

BLAINE No. Nobody gets Mr. Buford to help...You basically have to teach yourself physics.

His immediate negative response ("No") indicates that Blaine does not tend to invite Mr. Buford's perspectives during class. He does not see asking questions to the teacher as an option. From the in-class data we see that Beck, Ed, and Otto often engage with Mr. Buford and ask him for help, but yet Blaine still says, “nobody gets Mr. Buford to help.” This could indicate that he does not view the interactions as helpful, which would mean that Blaine often does not see the insights that emerge from interactions. The last utterance he gives in his answer, “you basically have to teach yourself physics,” confirms that he tends to think of learning physics as a solo endeavor as opposed to a process influenced by others. There is a pattern of Blaine being disinterested in asking for help or feeling as though he cannot ask for help. Whatever the reason for this reluctance, it still shows that he does not value collaboration enough to overcome his uneasiness with asking for help.

During class, the developing nature of his willingness to collaborate was not as obvious. There were only a few instances where we coded Blaine’s collaboration (six times compared to 16 times for Otto, with whom Blaine sat together at a table), indicating that he often was working solo and did not “do” much to demonstrate a key inclination, sensitivity, ability, or lack thereof. We first examine an excerpt in which Blaine’s non-verbal actions speak to his avoidance of collaboration. We used it earlier to demonstrate Blaine’s lack of persistence.

Blaine.In-class.3:

BLAINE How do you make position a vector?

(3.5)

BLAINE It says position °must be a vector°

(6.5)

BLAINE **((stands up to gaze over Beck’s shoulder))**

(26.0)

BLAINE I cede

The half-minute when he gazes over Beck’s shoulder in search of an answer to his question indicates that Blaine had no interest in negotiating a shared understanding. His actions were oriented towards only absorbing an answer.

At other times, when he did say or do something that represented an effort to collaborate, other students did not take Blaine up on his offer to work together. In particular, his tablemate Otto often ignored what Blaine had to say. This could be explained by Otto's alertness to the fact that interacting with Blaine often impedes progress, because Blaine is often a source of distraction during class. An example of Blaine trying to engage with Otto about the activity is below.

Blaine.In-class.4:

BLAINE What are you trying to do? You trying to find the angle that you're gonna need to, refract it by?

Blaine's question represents an effort to collaborate by clarifying and questioning Otto's course of action to which Otto gives no response. However, before Blaine asked the question above, Blaine spent 20 of the previous 25 minutes telling jokes while Otto tried to focus. Three times during class, Otto told Blaine, "shut up." The final time, Otto had to cut off a three-minute-long joke about sombreros, saying "Shut up! I'm trying to think through this." Even when Blaine makes potentially genuine efforts to collaborate like above, it is in Otto's best interest to ignore Blaine because he is known for derailing the conversation into sources of distraction.

This reputation can sometimes come at a detriment to Blaine's credibility when he does make reasonable suggestions. Below is an example where Blaine's surface-level recommendation for Otto's code went completely unheard.

Blaine.In-class.5:

OTTO \$To be honest I don't [ra-\$

BLAINE [No dude just ah- y- you got it.

OTTO That's a good step though.

BLAINE **Now just hit a negative sign.**

(30.0)

OTTO Oh, [because it needs to be. Negative. Ah: that's why

BLAINE **Isn't that literally what I said?**

OTTO [I don't know.

BLAINE [I told you just make it negative.

OTTO **No. No the y needs to be negative.**

BLAINE **That's what I said.**

OTTO ((coughs)) *I wasn't listeni:ng*

This excerpt sees Otto stuck on a coding issue. He had just figured out how to get a particle to move on screen, but it was going in the opposite direction than he wanted. Blaine made a surface-level suggestion for a fix: "just hit a negative sign." He notably did not specify where or how the negative sign should be applied, nor did he provide any justification for the benefits of his suggestion. Otto did not react, but 30 seconds later he announced a realization that all he needed to do was make "it" negative. Blaine claims that that was "literally" what he said, even though Otto specifies it was a y-value that "needed to be negative." Blaine said nothing about a y-value, but Otto "wasn't listening" anyways. The disagreement blows over, but it highlights an instance where Otto was not listening to Blaine despite Otto's high willingness to collaborate. An explanation for this is that Blaine is not taken seriously as a potential collaborator because of his previous behavior in class.

This points to the collaborative dilemma in which Blaine has ended up. Blaine's tendency to not take the computational activities seriously is likely tied to the tendency for his peers to not take Blaine seriously. Blaine demonstrated throughout the data that he has a developing willingness to collaborate with others, as shown by his unwillingness to have his course changed by interactions with others, his inability to listen to and have his actions shaped by others, his inability to articulate or justify the benefits of a particular approach, and his inability to negotiate a shared understanding. Blaine's infrequent efforts to actually collaborate are almost always ignored by his peers, even though these efforts sometimes represent instances where Blaine seems aware of the unique insights that emerge from interactions, able to listen to others, and able to negotiate a shared understanding. These efforts are short-lived and do not inspire his peers to try collaborating with Blaine, which is why we believe overall that he represents a developing disposition for collaboration, though

	Tolerance for Ambiguity	Persistence on Difficult Problems	Willingness to Collaborate with Others
Ed Interview	6 high 9 developing	12 high 4 developing	6 high 3 developing
Ed In-class	4 high 0 developing	8 high 2 developing	20 high 3 developing
Ed Total	**10 high** **9 developing**	**20 high** **6 developing**	**26 high** **6 developing**

Table 7.7: Coded instances of dispositions for Ed, separated by data source and tallied.

perhaps not as low on the spectrum as his other dispositions. Ultimately, Blaine demonstrated that he was on the developing end of the spectrum for all of the dispositions (tolerance for ambiguity, persistence, and collaboration).

7.7.1.3 Ed Disposition Profile

In contrast to both Blaine and Otto, Ed demonstrated a mixed disposition for tolerating ambiguity and mid-to-high dispositions for persistence and collaboration. The codes for her interview and in class data are summarized in Table 7.7. Notably from this table, she had far more codes for tolerance for ambiguity in her interview, and these codes tended to be much more developing than they were for her in-class data. Also, Ed had far more codes for collaboration in her in-class data. We address these features of her data set and more as we proceed to present her case and demonstrate how the spectrum of dispositions occurred among her data.

7.7.1.3.1 Ambiguity

Ed's tolerance for ambiguity seems to be in the middle of the spectrum, perhaps leaning towards a high tolerance. In her interview, she made many statements aligning with a disposition for a developing tolerance of ambiguity, but in class, her statements tended to align with a high tolerance. For example, there was a moment in her interview when she discussed a challenging example from the optics unit. In describing her difficulties, she framed the ambiguity of optics as a source of confusion.

Ed.Interview.1:

> ED [Optics] was just incredibly confusing for me. Literally just the sign convention, it was so- I don't know why, there was just something weird to me about how **if you got closer or farther from a lens, the image could literally be flipped upside down, depending on what kind of lens it was.** And what you would mark that as for the focal point, is it negative or positive, or where? And like mirrors and lenses and how, I think, **if an image is on the same side for a mirror, it's a positive image whereas if it's on the same side for a lens it's negative. It was just too much.**

Ed was not able to make sense of the new material. Particularly, the sign convention of the focal length equation tripped her up. She went on to describe the different rules of the sign convention, e.g., "flipped upside down, depending on the lens" and "if an image is on the same side for a mirror, it's a positive image, whereas..." The complicated rules that Ed seems to have committed to memory indicate that she is trying to put optical situations into rigid categories. She seems to be overwhelmed by the task to remember all this: "it was just too much." Despite her awareness that her current approach was overwhelming, she never successfully took up an opportunity to reframe the complicated, ambiguous relationship between the equations and concepts.

When it came to computation, Ed displayed a similar stance towards ambiguity. The excerpt below is a reflection she made on her relationship with computation in Mr. Buford's class.

Ed.Interview.2:

> ED GlowScript especially, I feel like **it caters to a very specific kind of learner**, a very specific way of learning physics that's like oh, if you- it just requires you to take apart the numbers in a very strange way. Well, **it's not a strange way, it's a strange way for me.**

In Ed's view, "taking apart the numbers" during computational activities is not something she was cut out for. She said that learning physics through GlowScript "caters to a very specific kind of learner," indicating a rigid, inflexible categorization of who benefits from the new computational activities. When she acknowledged that computation may not actually be that strange, just "a strange way for me," she framed computation as something not for her. The reason, in Ed's view, was computation's strangeness. This indicates a lack of interest in exploring and undertaking the strange (messy) parts of computation.

Though there were numerous instances of negativity towards ambiguity, Ed also had the ability to see the benefits in the ambiguous parts of computation. In class, we saw her behavior represent a high tolerance for ambiguity, in contrast to the statements in her interview. For instance, the excerpt below shows Ed making some considerations about changing the variable that represents velocity in her code. She talks to herself and asks questions to herself throughout the excerpt, only once directing a question to Beck, which he answers promptly. At multiple times, she demonstrates an ability to navigate the uncertainty of the situation.

Ed.In-class.1:

ED	=Should I just make the velocity a scalar? Possibly
	(4.5)
ED	Should I make my velocity maybe a scalar and just do ah- °I can like°, **<u>I</u> <u>don't</u> <u>know</u> how that would work though**
	(8.0)
ED	You have velocity dot x?=
BECK	=**Velocity's a vector** so this should (inaudible)
	(8.0)
ED	Actually, **maybe I might have something (11.0)**
ED	**((hums and sings to self))**

She begins by wondering out loud whether velocity could be represented with a scalar quantity in her program. She admits, “I don’t know how that would work,” which tells us there is significant uncertainty in this situation. Once Beck confirms that “velocity is a vector,” Ed appears to be able to figure out a path forward (“maybe I might have something”) and seems committed to implementing the new idea, as indicated by the eleven seconds that pass and the humming to herself, which is a marker throughout the class period that she is focused on the code. Altogether, this demonstrates a navigation via an uncertain trajectory towards a solution.

Overall, the contrast between Ed’s interview and in-class data shows that students need not always exhibit the same level in a disposition. Ed displayed in her interview a tendency to rigidly categorize, an unawareness of opportunities for reframe ambiguous situations, and an inability to find value in undertaking messy tasks. However, in class she showed that was capable of navigating incomplete data and uncertain trajectories toward a solution. This suggests that Ed may have a different understanding of her conduct than she displays in class. Either way, she is capable of approaching computational activities with a high tolerance for ambiguity even though she may articulate in her interviews a disposition that is skewed towards a more developmental tolerance.

7.7.1.3.2 Persistence

Ed has a disposition for high persistence. There were several moments during her interview where it was clear that she tends to persist in nearly all the endeavors she takes up. For example, she is “the only remaining programmer on my robotics team,” and her mom encouraged to persevere through tough initial experiences with physics (last year) and violin (eight years ago). When analyzing for key aspects of persistence in her interview and in class, the findings confirmed this interpretation. For example, Ed discussed the satisfaction that comes from getting a class project to work.

Ed.Interview.3:

Ed Sometimes when we’re doing projects and in just **the rare moment that it just goes okay, that feels good.** And you feel it.

Int Nice. Can you describe a moment in a project like that?

ED Yesterday. We recently got projects like to make a telescope, basically, which is two converging lenses, and it just worked. **We just made it, and it just felt good.** It's like we found the- It's just two paper towel tubes, basically, and we just put them on either end and just focus it, and it just worked. And that was a good moment. Even though- Oh, gosh. But even though **we had worked for a whole two days on it, because the first day we were trying to put an actual model of something between, like a phone, and it was awful.** That was a bad day.

She first nods at the good feeling before describing an example: "the rare moment that it just goes okay, that feels good." She says this again in reference to completing the telescope project: "We just made it, and it just felt good." These utterances demonstrate Ed's awareness of the satisfaction derived from success after significant effort. We know she put in significant effort because she described "working for a whole two days on it," which points to her ability to stick with a task for an extended period of time. This excerpt also demonstrates Ed's ability to try a new approach after considerable effort—she described working for the first day "putting something between like a phone," which was an "awful" approach that failed, and then she shifted to the paper towel tubes method.

That said, there were a couple points where Ed showed a developing persistence in her interview, including when she described giving up in the midst of confusing aspects of computation.

Ed.Interview.4:

INT Do you think you're good at the coding activities?

ED Not really, actually, which is kind of sad for me to be honest, because you have this interest in something, but it's back to why physics is so frustrating, because It's something that's like **'Oh, this is familiar, I know this,'** but then you just- It's just slightly slanted a little and just becomes, because **you expect it to be this way so much, when it's this way, it's just- you can't handle it.**

The confusion she describes in this excerpt is unexpected confusion: "you expect it to be this way so much, when it's this way, it's just- you can't handle it." Ed has perceived a "familiarity" with the computational tasks, and then that familiarity is betrayed, leading her to give up in the moment: "when it's this way, it's just- you can't handle it." Instead of taking the opportunity to shift tactics or reframe the problem, Ed is unable to change her approach during the confusion.

The occurrence of the above confusion and disengagement is rare given Ed's statements of mostly high persistence in her interview. When examining the in-class data, we confirm her high disposition. During class, she is consistently considering new ideas to implement in the code or new ways to deal with a roadblock. The first instance of this is when she wasn't sure how to model a light particle with a visual object in GlowScript, so she entertains an idea to model it as a sphere:

Ed.In-class.2:

ED **What the $fu:ck$**

(10.0)

ED °I'll just do::° Okay **I'll just do a sphere, trail**, okay I got this, it's fine, it's cool

(41.0)

ED °Make the trailer true:° ((clears throat))

(7.0)

ED °So we'll do lines°

She begins with a statement of confusion ("what the fuck") and then moves on to consider an option for modeling the particles with a sphere. Over the next 41 seconds, she works, and her next utterance indicates she is still on the same task, as "trailer" refers to the sphere's trail that she mentioned earlier. The initial consideration to implement a "sphere" after being stuck indicates that she was attentive to an opportunity to try a new tactic.

At a later time about halfway through the class period, she arrived at the need to implement a while-loop in her code. She proceeded to engage Beck in one utterance of conversation and then worked on the loop herself, once looking at Beck's code for additional help.

Ed.In-class.3:

ED **How do I do a LOOP.** ((laughs one exhale)) °**time to just (inaudible) Beck's (inaudible) things°.** So velocity::

BECK Huh. Why don't you put a [focal point (inaudible)?]

ED [(inaudible) like]. V:ector

(4.5)

ED In the: x direction and not in any other direction cause we not about that bullshit

(9.0)

ED **((glances at Beck's laptop)) I always forget d t too,** alright. And then, °**let's move**°

In the first line, her intentions aren't exactly clear due to the inaudible speech, but she announces her need to create a loop and then acknowledges that it's time to do something involving Beck. We infer that Beck's code or expertise is desired, because Beck answers her comment in the next line, and later on Ed glances at his code while trying to implement the while-loop. This represents a pursuit of resources (Beck's insight and Beck's code) that increase the effectiveness of her efforts. This glancing at code is different from Blaine.In-class.3 (when Blaine gazed over Beck's shoulder) because Ed's glancing was an enhancement (reminding her of "d t") of the effort and interaction that she was engaged in; whereas, Blaine's gaze was the only activity he was engaged in, and he was trying to find answers as a substitute for engaging in collaboration and/or effort.

Despite her persistence throughout most of the class period, when Mr. Buford asked Ed a question about her progress near the end of class, her response demonstrated some negativity against persistence.

Ed.In-class.4:

MR. BUFORD Did you get something going?

ED Not really, to be honest. **I was just, staring at it in the hopes that it would make sense**

Her summary of what she did for all of class is about trying to absorb information and indicates no overall change in strategy or attentiveness to shift tactics when needed. "Staring at" the problem also indicates no desire to apply extended effort to the computational activity. This account doesn't match with her conduct throughout the class period, which means she is not accurately representing her work with this statement, though this statement could be how *she* is interpreting events.

Overall, we see that Ed has a disposition for high persistence, as shown by her awareness of the satisfaction of effort paying off, her attentiveness to opportunities to shift tactics when needed, her ability to stick with a task for an extended period, her ability to try a new approach after considerable effort, and her pursuit of resources that increase the effectiveness of her effort. At times she either did not recognize her own persistence, or she wished to represent her workflow more modestly or more in line with how she is feeling in the moment. This was the case in Ed.Interview.4 and Ed.In-class.4, where she demonstrated an inclination *against* extended effort and did not seem attentive to opportunities to shift tactics. This handful of examples of developing persistence contrasted with and was overshadowed by her generally high persistence, which is why we claim Ed had a persistence on the higher end of the disposition spectrum.

7.7.1.3.3 Collaboration

Ed also has a relatively high disposition for willingness to collaborate with others, though infrequently she displays a developing willingness. Below, she describes her tendencies to work with others but also to trade answers transactionally.

Ed.Interview.5:

INT So in general in class, do you tend to work by yourself, or like in a group of students?

ED **I don't think I've ever once worked by myself, to be honest.**

INT Okay. Maybe a test, yes?

ED Yeah, a test.

INT When you work with your classmates, what role do you play in doing group work?

ED I feel like **I kind of just leech off people, to be honest. Like if I just don't know an answer, I'm just going to ask around until someone gives me the answer.** Just being completely honest.

INT Okay. Are there times you do know the answer, or you know part of what you need to do?

ED Yes. Beautiful, happy times.

INT Okay. And is your role different when that's the case?

ED Yes. Then **I get to tell people the answer.**

She starts with a fairly strong statement: "I don't think I've ever once worked by myself, to be honest." This indicates that Ed often invites the perspectives of others into what she is doing, and she is willing to let these interactions change the course of her work. She goes on to describe how she feels that her role is to "leech" answers from her peers. The practice of taking answers without contributing to them indicates simultaneously a willingness to let others shape her actions and an inability to negotiate the understanding that the group is building. Even when she can contribute, it's still just answer-giving: "I get to tell people the answer." The implication of "giving" the answer is that she does not articulate the explanation behind the solution or justify its benefits. However, when we asked for her to clarify this peer group dynamic, it turned out that the answer-transfer practice was actually a result of attempted-but-failed explanation of answers:

Ed.Interview.6:

INT Is it ever like, explaining how the answer is, or explaining how it works, or is it just like 'this is the answer'?

ED I feel like **we all attempt to explain.** I've noticed some people try to explain to me and like **'I didn't get that, but I believe you,'** and it just works. And I'll try to explain it to them and they'll be like **'I don't understand what you're saying.'** So we try, it doesn't really work, though.

The "attempt to explain" indicates that Ed and her peers actually do try to articulate and justify the approach behind the answer they are trying to share with the group. However, these attempts fall flat—responses include "I didn't get that" and "I don't understand what you're saying." This failure to communicate understanding indicates that Ed (and her peers, according to her) does not have an alertness to the interpersonal dynamics she might be able to leverage in order to make these interactions more effective.

When we looked at the in-class data to further understand the nature of her group work, it seemed that she was much more collaborative than she gave herself credit for, and the "leeching" relationship did not play out so transactionally. Ed collaborated openly and often. For example, shortly after the beginning of work time, she checked in with her tablemates ("So how's everyone doing?"). Later in class, she engaged in a conversation with Beck about visualizing rays of light ("lines", below).

Ed.In-class.5:

ED You know what? It's a dot, we're getting there, we're doing okay

BECK That's good

ED Thank you

BECK If you don't want your lines to be so dark, you can give em a thickness. (inaudible) ((points at Ed's screen))

ED Oh yeah

BECK If you just go to size and make that one, the: zero

ED **Make the zero one=**

BECK =Yeah=

ED =**Oh: true you're right!**=

BECK =For, for the lens [and the optical axis]

ED [**So it's not transparent**]

BECK And then, same here with the lens- no not there, not there, [°not there°

ED [Right

The conversation revolves around Beck's suggestion to thicken some lines in her visual so they would be easier to see. Ed accepted Beck's suggestion with excitement ("Oh: true you're right!"), which indicates a responsiveness to the contributions of peers. She also made comments as Beck explained ("make the zero one", "so it's not transparent") to follow along, and this demonstrated tendencies to both clarify the understanding he was providing and to value his perspective on this matter.

At another time, Ed checked in with a struggling group member, Brian.

Ed.In-class.6:

ED **How are you doing Brian?**

BRIAN Huh, what?=

ED =**I said how you doing?**

BRIAN Terrible

ED Amazing

(2.0)

ED Is that just your response to anything that- I thought this was gonna be a &deep conversation about **our shared struggle with, writing this glow script**&

Her question ("how are you doing Brian?") demonstrates an interest in the well-being of her peers. When Brian responds negatively and with only one word ("terrible"), Ed explains that she is open to sharing in the struggle of the computational activity. This indicates an alertness on Ed's part to the interpersonal dynamics that could make interactions more worthwhile. In this case, the implication is that checking in with others can benefit interactions within the group. Her offer to share in Brian's struggles also shows that Ed is not always just giving or taking answers like she indicated in her interview. Ed has a connection with her classmates, and her collaboration in class went beyond just the moments when Beck helped her figure something out.

When reviewing the key inclination, sensitivities, and abilities of collaboration, Ed displayed several in the excerpts above: a willingness to have her course changed by interactions with others, a tendency to invite and value perspectives different from her own, an alertness to effective interpersonal dynamics (in the case of checking in with Brian), a responsiveness to the contributions of peers, and an ability to clarify and negotiate a shared understanding and course of action. She also demonstrated, in describing how she shares answers with peers in Ed.Interview.6, an earnest attempt to articulate and justify the benefits of a particular approach. This answer-sharing that Ed engages in also relates to some developing aspects of collaboration: an unawareness of how to enhance the effectiveness of interactions, an inability (even through her earnest attempts) to articulate and justifying the benefits of a particular approach, and an inability to negotiate a shared understanding. The fact these developing codes did not bear out hardly at all in the in-class data suggests that Ed's disposition for collaboration is higher than she is aware of in the interview setting.

Overall, Ed demonstrated mid-to-high dispositions on each spectrum. She had a high willingness to collaborate, a high persistence, and a split tolerance for ambiguity, with many high statements coming from the in-class data while in her interview she articulated more of a developing tolerance for ambiguity. There were also moments where Ed played down her persistence and collaboration, even though the patterns in the data and the examples we provided show high levels of both dispositions. Her treatment of the dispositions suggest that she is slightly modest or not fully aware of how much her behavior aligns with high dispositions.

7.7.1.4 Summary of Dispositions Results

To summarize the results of our disposition profiles and corresponding analysis, we found examples of dispositions in Mr. Buford's class from across the spectrum. Otto's interview comments and in-class behavior aligned with high levels across all three dispositions, with perhaps some small developing tendencies to his dispositions. For example, he sometimes does not recognize or experience a sense of satisfaction after persisting through a difficult computational task. He also indicated that he was less willing to collaborate in a setting where he held more expertise – calculus. In contrast, Blaine's interview comments and in-class behavior indicated developing levels across all three dispositions. His in-class behavior seemed to build a reputation for not taking the computational activities seriously, which made it difficult for him to collaborate with others even on occasions when he did have questions. Ed's comments show how a student may be at a mid-point on the dispositions spectrum. Sometimes she talked about her behavior in a way that indicated more of a developing disposition for her tolerance toward ambiguity, whereas her behavior in class was more closely aligned with a high disposition. Overall, she had high levels of persistence and collaboration and a mixed tolerance for ambiguity. Similar to Otto, Beck showed high dispositions across all the categories (discussed in detail in Appendix A). Beck's interview comments and in-class behavior indicate a high tolerance for ambiguity and the highest levels of persistence and collaboration (*zero* developing codes!). For ambiguity, Beck displayed a high tolerance but also articulated that he preferred when activities were more clear-cut and oriented towards a single solution.

We also use this summary section to provide Table 7.8, which shows how the disposition codes were split between data sources and between key inclinations, sensitivities, and abilities. In short, tolerance for ambiguity was more likely to show up in the interview setting, key inclinations for persistence were rarely observed at all, and key abilities for collaboration were overwhelmingly found in the in-class setting. When we examine Table 7.8 in more detail, we notice that tolerance for ambiguity was more likely to show up in interview comments, indicating that assessing for this disposition should involve some sort of reflective activity (like the interview) for students rather than trying to observe their behavior directly. We also noticed that inclinations for persistence were rare, which could mean there is another data source we did not consult that could have provided information about students' inclinations for persistence. Lastly, the in-class data (instead of the interview setting) was where students exhibited collaborative abilities, indicating that this aspect of collaboration *can* be observed directly, as long as students have opportunities in class to collaborate

	High Disposition		Developing Disposition		**Total (High and Developing)**	
	Interview	In-class	Interview	In-class	**Interview**	**In-class**
Ambiguity Inclinations	11	5	16	5	**27**	**10**
Ambiguity Sensitivities	21	8	3	4	**24**	**12**
Ambiguity Abilities	16	11	9	3	**25**	**14**
Ambiguity Overall	**48**	**24**	**28**	**12**	**76**	**36**
Persistence Inclinations	2	1	3	4	**5**	**5**
Persistence Sensitivities	17	15	4	5	**21**	**20**
Persistence Abilities	17	16	5	3	**22**	**19**
Persistence Overall	**36**	**32**	**12**	**12**	**48**	**44**
Collaboration Inclinations	11	11	4	0	**15**	**11**
Collaboration Sensitivities	4	11	4	3	**8**	**14**
Collaboration Abilities	10	32	4	4	**14**	**36**
Collaboration Overall	**25**	**54**	**12**	**7**	**37**	**61**

Table 7.8: Codes for inclinations, sensitivities, and abilities are separated out among the dispositions for comparison. The codes are binned by data source. The left four columns are separated between high and developing dispositions, and the right two columns simplify the information by providing counts that combine high and developing codes for each disposition.

with one another.

7.7.2 Mindset Results

In this section, we explore how the mindset framework relates to the dispositions framework in our data for each student. We also show how mindset was present in the data independent of the dispositions, which highlights how mindset can be ascertained even when dispositions are not obvious. This combination allows us to discuss for each student how mindset overlaps with dispositions and how it exists separately.

	Otto	**Blaine**	**Ed**	**Beck**
Interview	20 growth 3 fixed	4 growth 26 fixed	10 growth 11 fixed	14 growth 1 fixed
In-class	10 growth 1 fixed	0 growth 20 fixed	7 growth 8 fixed	6 growth 0 fixed
Total	**30 growth** **4 fixed**	**4 growth** **46 fixed**	**17 growth** **19 fixed**	**20 growth** **1 fixed**

Table 7.9: Coded instances of mindset for each student, separated by data source and tallied. The bottom row provides a total count of fixed and growth mindset codes for each student.

7.7.2.1 Otto Mindset Results

In Section 7.7.1.1. 1, we showed how Otto had high levels of all three dispositions, though there was an exception to his high persistence since he indicated little satisfaction at completing especially difficult computational activities at times. Building on this analysis, we now show how mindset was present in his data (as shown in Table 7.9), providing a few examples from both in and out of our dispositions framework.

The first excerpt we return to is Otto.In-class.3, where Otto recruits Beck's help to interpret and deal with an error message. With the disposition analysis, we used this to show that Otto had a sensitivity and ability for shifting tactics as well as an endurance for sticking with the task at hand. These codes demonstrated his high persistence. In this same quote, we also see a few codes for growth mindset. Otto had an immediate reaction to the error message: "Why is that wrong? Beck. Why is it undefined?" The choice to draw attention to the mistake and bring Beck into the fold was both an opportunistic tactic shift AND a desire to learn. Otto demonstrates a tendency to view the setback as an opportunity to learn and overcome rather than a paralyzing roadblock.

In Otto.Interview.7, Otto explained a view that the "smartest" students in class are also the best explainers of physics concepts. With the disposition analysis, we coded this for Otto's sensitivity to how explanation presents an interpersonal dynamic that helps students work together, which also indicated Otto's high willingness to collaborate with others. In the quote, Otto talked about two students, Beck and Joyce: "If you could say one person was an explainer type guy, it's [Beck]... [Beck and Joyce] tend to be the ones who are able to express [problems and concepts] to other people." This shows that Otto values understanding over answers because of how he attributes Joyce's and Beck's competence to their ability to explain, not to their high grades. Otto's high valuation of understanding aligns closely with an aspect of growth mindset, "learning is important."

Outside of the excerpts we analyzed for dispositions, there were also instances where Otto displayed a growth mindset. For example, the excerpt below is from Otto's interview, and precedes Otto.Interview.3. The interviewer asked whether Otto felt he was good at the computational activities.

Otto.Interview.Mindset:

INT Do you think you're good at the coding activities?

OTTO **I'll get better.** I'm not very good at it right now.

INT Have you noticed yourself getting better even in the last couple of months?

OTTO Yeah, I'd say so. **I'm starting to understand** like the- well, Python syntax for one is weird. I like Java more.

Otto did not express a high self-evaluation, but what matters here is that he expressed a belief that he would "get better." This encapsulates a belief that his skill at computation can be grown. Even though he admits that what he is learning is "weird," he also can see that he is "starting to understand" it. Otto's comments here show that he can sometimes indicate explicitly a growth mindset without displaying dispositions for ambiguity, persistence, or collaboration.

Using all of the data from Otto's interview and the in-class data, we can construct the diagram in Figure 7.2, which reflects how Otto's excerpts were coded for dispositions, mindset, and sometimes both at the same time. We introduce it here to point to how mindset exists with and without dispositions in Otto's data. Fourteen out of the 32 excerpts coded for mindset were also coded for dispositions, indicating a significant overlap between the frameworks in Otto's data. On the other

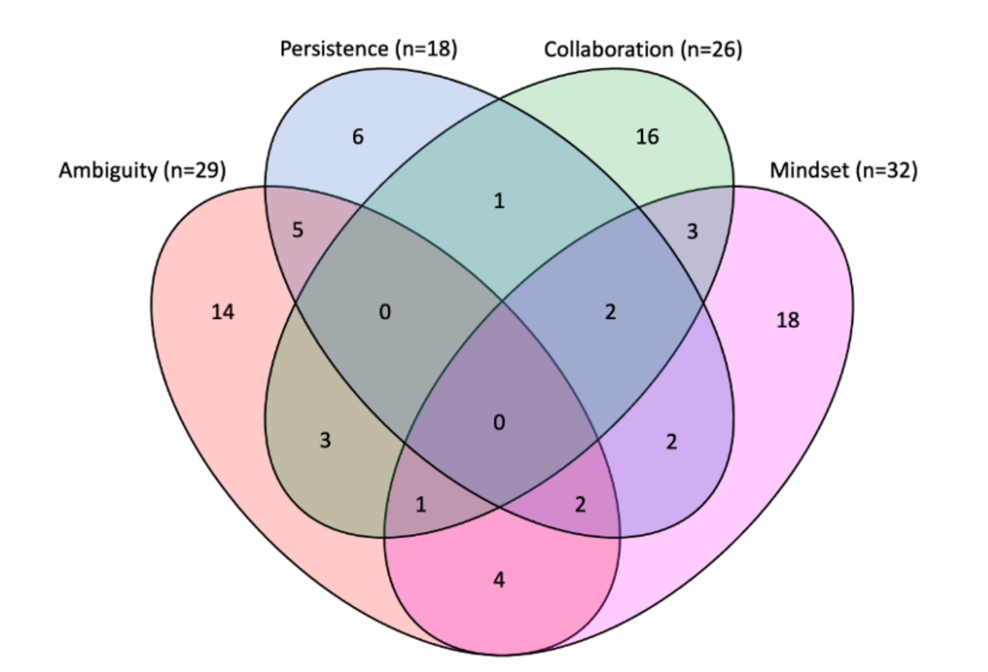

Figure 7.2: Venn diagram showing the number of coded excerpts in Otto's data that overlapped between mindset and each of the three dispositions, including overlaps between the dispositions themselves.

hand, 18 out of the 32 excerpts coded for mindset were *not* coded for dispositions, which suggests that although mindset and dispositions can coexist, they are not the same thing, and often mindset can be present in what students say and do when dispositions are not.

7.7.2.2 Blaine Mindset Results

In contrast to Otto, Blaine displayed developing levels across all three dispositions. When we looked at how mindset was present in his data, both in and out of our dispositions analysis, we found that Blaine heavily made fixed mindset statements (See Table 7.9).

For example, in the Blaine.In-class.2 excerpt, Blaine ran some code, received an error, exclaimed that he "[didn't] know how to code," and then searched online for answers to copy. In the dispositions analysis, we showed that this was an example of Blaine's inability to take up an opportunity to grow by engaging with an uncertain situation and an indication of his lack of interest in reframing ambiguous stimuli. In this same excerpt, there are also some indications of a fixed mindset. When

Blaine evaluated himself as “not knowing how to code” after receiving an error message (something that happens to *everyone* who codes), he is interpreting this small mistake as a message that he is bad at computation. This is characteristic of fixed mindsets (seen in Table 7.2). Also, his decision to look for “sample code” online instead of confronting the error indicates that he is trying to avoid thinking hard about this activity. As a note, looking for sample code can be considered a legitimate strategy in computation, but the circumstances explained above indicate that Blaine is doing this without depth or direction; instead, he is looking for the "right" answer online.

Similarly, in the Blaine.Interview.5 quote, Blaine described how he tried to code correctly countless times in the past without any success, and he doesn’t try anymore because of his continued failure. He always seems to get “a blank screen or...some error” whenever he codes. In the dispositions analysis, we interpreted this comment to mean that he was unable to shift his approach in the face of constant failure, indicating low persistence. There are also indications of a fixed mindset: his choice to not try anymore shows that his failure has made him less interested in computation, and his inability to proceed after receiving the error shows that he is paralyzed by setbacks.

We also saw evidence of Blaine’s fixed mindset independent of the dispositions analysis. For instance, when we prompted Blaine to reflect on a statement he made near the end of class, he responded:

Blaine.Interview.Mindset:

INT I’m going to read you a quote that you said on Monday. I want you to unpack it for me a little bit. The quote was, **‘What’s the point of learning code? I can draw this on a piece of paper in fifteen seconds.’**

BLAINE I did say that...I could draw it on a piece of paper in fifteen seconds. Okay? All right? That’s how I was feeling at the time. **Just have a line, make it curve**. I can do that, real quick. I didn’t mean learning code in general, but doing this code, **this code’s wackeroonie.** Whatever.

INT Just this specific project that you were working on at the time?

BLAINE Yeah, I'm sure code could be applicable in a lot of places but **I don't need to plug it into a computer to draw some straight lines.**

In the excerpt, Blaine defends his judgment of the computational activity. He emphasizes that the point of the activity was, "just have a line, make it curve," which is something he could easily do on a piece of paper. He went further into his evaluation of the activity, saying, "this code's wackeroonie," which we take to mean that he saw the activity as convoluted and/or pointless, an evaluation of the assessment as unfair (and an indicator fixed mindset, as shown in Table 7.2). Blaine's insight into his comment shows that he has no desire to engage with the challenge of computation because the same visual can be achieved by drawing it: "Just have a line, make it curve. I can do that, real quick...I don't need to plug it into a computer to draw some straight lines." This avoidance of taking up the opportunity to try plugging what he knew into the computer signals an avoidance of the challenge, which is an indicator of a fixed mindset (see Table 7.2).

In class, Blaine's behavior also pointed to a fixed mindset. The excerpt below happened directly after Blaine.In-class.1. In it, Blaine is commenting on how he thinks GlowScript should work and highlighting his inexperience with computation compared to his table mate Otto.

Blaine.In-class.Mindset:

BLAINE That's how it should be. If I put in line, a line should appear. I don't understand why it doesn't, you know?

BLAINE I personally think **whoever made this &glow script& didn't know what they were doing**

(11.5)

BLAINE &**Just a note for the record,** Otto has taken a, coding class, at this school. It's AP computer science&

OTTO I was bad at it

BLAINE &He might've learned a few things, he got an A in the class&

OTTO I was bad at it

BLAINE &Most kids failed it. But um, that's why he has a little bit of an advantage on me. You know **I've never even seen a code before, what is a code?**

The first line in this excerpt is the last line in Blaine.In-class.1, and it is an instance of Blaine expressing his disapproval of how GlowScript works. He thinks it should draw a line when he types "line." His next statement is what we code for mindset: "whoever made this &glow script& didn't know what they were doing." His emphasis on "they" implies a switch: earlier, Blaine admitted, "I don't understand," and now he is emphasizing "they" to indicate that the designers of GlowScript are the ones who *actually* messed up. This indicates that Blaine is avoiding responsibility for his recent failure. He goes on to contrast his preparation against Otto's. Blaine has no prior academic experience with computation, and he leans hard into this narrative: "I've never even seen a code before, what is a code?" He frames this disclosure as "a note for the record," which indicates that he does not want to come across as stupider than Otto, it's just that he has less experience. Blaine's choice to highlight his lack of experience is different from when Otto did so in his interview ("I'll get better. I'm not very good at it right now") because Otto framed his situation as something to improve on, whereas Blaine framed it as a lack of "advantage" that he could blame for his mistakes. Thus, we see Blaine deflecting responsibility for his failure at coding again. Overall, we see across data sources, in and out of the instances of disposition, that Blaine has a fixed mindset.

Despite the differences between Blaine and Otto, the Venn diagram of Blaine's coded excerpts in Figure 7.3 shows much of what Otto's did: mindset often showed up in Blaine's data even when dispositions did not (27 out 46 times). The times when mindset *did* overlap were also substantial: 19 out of 46 times. When looking at the overlaps, another notable feature of Blaine's coding is that it was rare for collaboration to be coded with mindset at the same time, only twice ever. We return to one of those instances in the discussion where we discuss why this may have happened in Blaine's data.

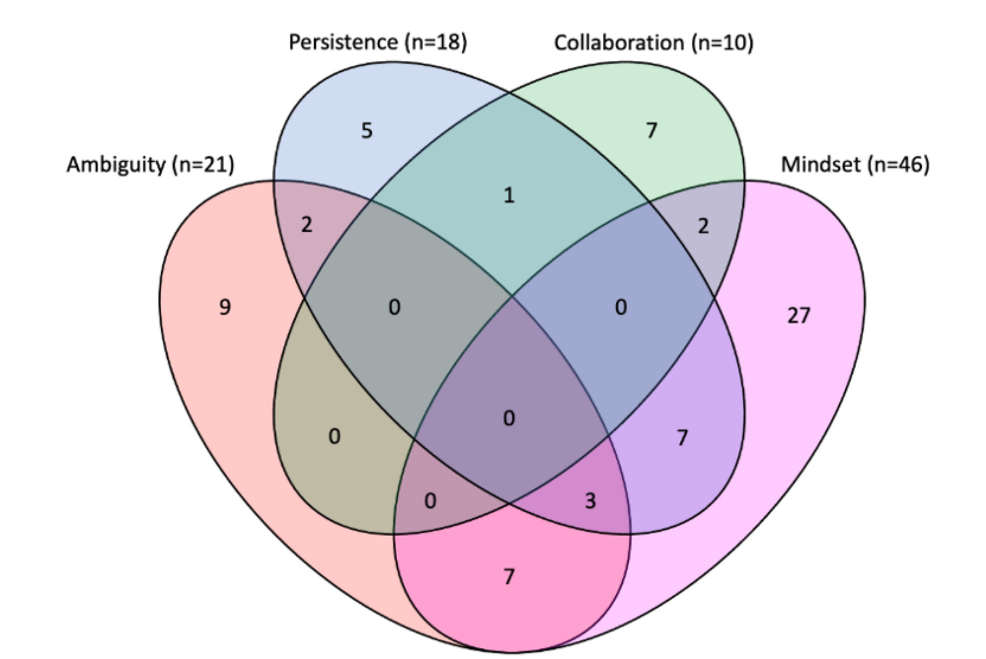

Figure 7.3: Venn diagram showing the number of coded excerpts in Blaine's data that overlapped between mindset and each of the three dispositions, including overlaps between the dispositions themselves.

7.7.2.3 Ed Mindset Results

Ed generally displayed mid-to-high levels of all three dispositions, representing a midpoint on the dispositions spectrum. Despite many high dispositions codes (especially in class), she indicated in her interview that she had a developing tolerance for ambiguity, and during class she summarized her work to Mr. Buford in a way that indicated a misunderstanding and/or modest interpretation of her persistence. Ultimately, we found that there was some misalignment in how she reported her dispositions versus acted them out, with the higher levels of dispositions more apparent in her actions. When we look at Ed's mindset, we see a similar story. Unlike Otto (who mostly had growth mindset codes) and Blaine (who mostly had fixed mindset codes), Ed's mindset codes were fairly evenly split between growth and fixed mindset (see Table 7.9).

For example, in the Ed.Interview.4 quote, Ed reflects about how computation feels familiar at first, but then it defies expectations and catches her off guard, leading her to feel like she "can't handle it." In the dispositions analysis, we coded this for an inability to change approaches when confronted with a confusing situation, indicating developing persistence. There is also evidence of the paralyzing nature of setbacks for Ed, because she makes the direct connection between the unexpected and losing control: "when it's this [unexpected] way, it's just- you can't handle it." This response to setbacks points to a fixed mindset.

At other times, she exhibited a growth mindset in how she responded to computation. For example, in Ed.Interview.3, she reflected on the satisfaction she felt from a difficult class project where she had to make a telescope. We coded this excerpt for Ed's ability to apply effort in the face of setbacks and for her awareness of the satisfaction derived from success after significant effort. These attributes of the excerpt point to high persistence, but they also convey a parallel to growth mindset. In particular, her sustained effort through a day of no progress ("we had worked for a whole two days on it, because the first day...was awful") indicated that the setbacks of the first day of the project were opportunities to overcome and succeed (growth mindset, see Table 7.2), which is what Ed did.

We see more evidence of mindset from Ed across the spectrum from fixed to growth in other parts of the data. In her interview, we discussed one of her favorite subjects, music, and compared it to physics.

Ed.Interview.Mindset:

INT What's a subject that you really don't like? If there is one.

ED I don't think there is one. They all have their ups and downs.

INT Okay. Is there one that you like significantly less or more than physics?

ED I can't really- Significantly less than physics, maybe- No, that's not true. Okay, nothing significantly less, but significantly more than physics, probably music, orchestra.

INT Music? Okay. How does your experience in music compare to your experience in physics?

Ed In physics, you kind of feel like- **A lot of what I feel in physics class is being almost kind of powerless as information is being fed to me**, I'm kind of not understanding it all the way, and in music you're like completely controlling the situation.

Int Okay. Yeah, that's a big difference. Are there things that you can do in physics that make you feel as if you have more control over the situation?

Ed **No. Just learn to deal with having no control.**

In this excerpt, a few features of physics class stand out compared to music. What Ed says almost speaks for itself: "A lot of what I feel in physics class is being almost kind of powerless as information is being fed to me." The feeling of powerlessness indicates that Ed feels no responsibility for her learning in physics class—a hallmark of fixed mindset from Table 7.2. When asked if she could do anything to change the power dynamic, she responded, "No. Just learn to deal with having no control." This cements our view that she doesn't see any control over her learning and doesn't see physics as something she can learn to do, which points to a fixed mindset.

However, during class, we saw Ed oscillate between a fixed and growth mindset when approached with difficulties. She would often voice out loud that she was stuck, or she was doing a bad job at the task at hand, yet still encourage herself to keep going. Below are three separate instances to demonstrate how she talks to herself in these moments.

Ed.In-class.Mindset:

Ed I'm do it- this is so bad

(4.0)

Ed Girlie. Get- get a grip on yourself

...

Ed I can't do this anymor:::e $heheher:$

(2.5)

ED Yes you can, you're doing fine, yes you're /fine/

...

ED °I can't /do:/ this. *I can't do this.* /Yes/ I can°

JOYCE You can do this Ed

ED I $can't though:$. *Today's not the day:* ((laughs one exhale))

Each time, Ed expresses a negative evaluation of her performance ("this is so bad", "I can't do this"), and then encourages herself to push past it ("get a grip", "you're doing fine"). This presents an interesting pattern of responses. When she first evaluates herself, it seems as if she is interpreting the situation to mean that she is stupid or that the setback is going to stop her from advancing (fixed mindset). However, each time, she encourages herself back into the task, indicating that she believes that she just needs to keep working or that the setback is something to be overcome (growth mindset). This flip-flop from fixed to growth mindset represents how Ed often displays features of both types of mindset at once, and it reflects how she sometimes indicates one level of disposition in her behavior and the opposite in a reflection on that behavior.

When looking at the overlap between mindset and dispositions in Figure 7.4, we see a pattern similar to Otto and Blaine, with 19 out of 31 mindset-coded excerpts coded for mindset alone. This suggests that there is both a significant difference and a significant overlap (though slightly smaller: 12 out of 31) between the constructs. We saw when analyzing for mindset (summarized in Table 7.9) that Ed held a mixed set of views between fixed and growth mindset, sometimes even rapidly oscillating between them (like in Ed.In-class.Mindset).

7.7.2.4 Summary of Mindset Analysis

In Figure 7.5, we provide a Venn diagram for the entire collection of data (including Beck, whose mindset analysis is shown in Appendix A) that show how the excerpts were coded with overlapping and non-overlapping disposition and mindset codes. While there seems to be a relationship between high dispositions and growth mindset, low dispositions and fixed mindset, and mixed dispositions

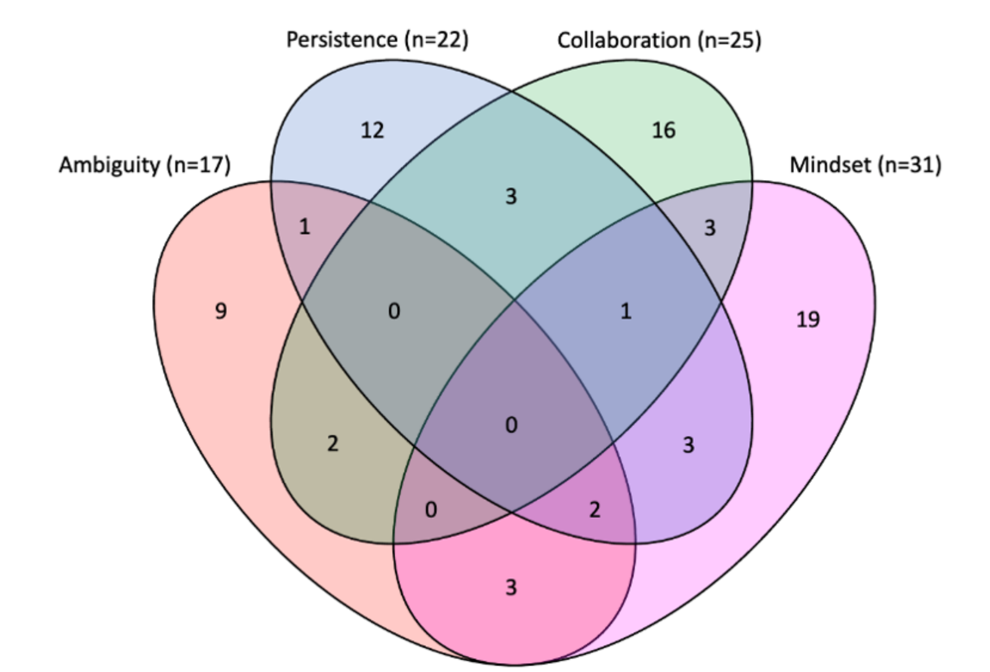

Figure 7.4: Venn diagram showing the number of coded excerpts in Ed's data that overlapped between mindset and each of the three dispositions, including overlaps between the dispositions themselves.

and mixed mindsets, there is no clear relationship between mindset and the individual dispositions. The overall trend shows that mindset is distributed across the dispositions (though slightly less for collaboration) when looking at excerpts that were coded for multiple constructs.

Furthermore, most excerpts coded for mindset were coded *only* for mindset (74 out of 125). This leads us to believe that mindset is a separate construct from dispositions, but nonetheless it is related. Though we didn't differentiate between high/developing or growth/fixed codes in Figures 7.2-7.5, it is notable that of the 50 excerpts that were coded for both mindset and dispositions, 46 were coded with aligning codes, meaning only high dispositions and growth mindset, or only developing dispositions and fixed mindset. This breakdown is shown in Table 7.10. This alignment between dispositions and mindset in the data shows that having high dispositions seems to be tied to having a growth mindset, even though the two constructs show up in different ways.

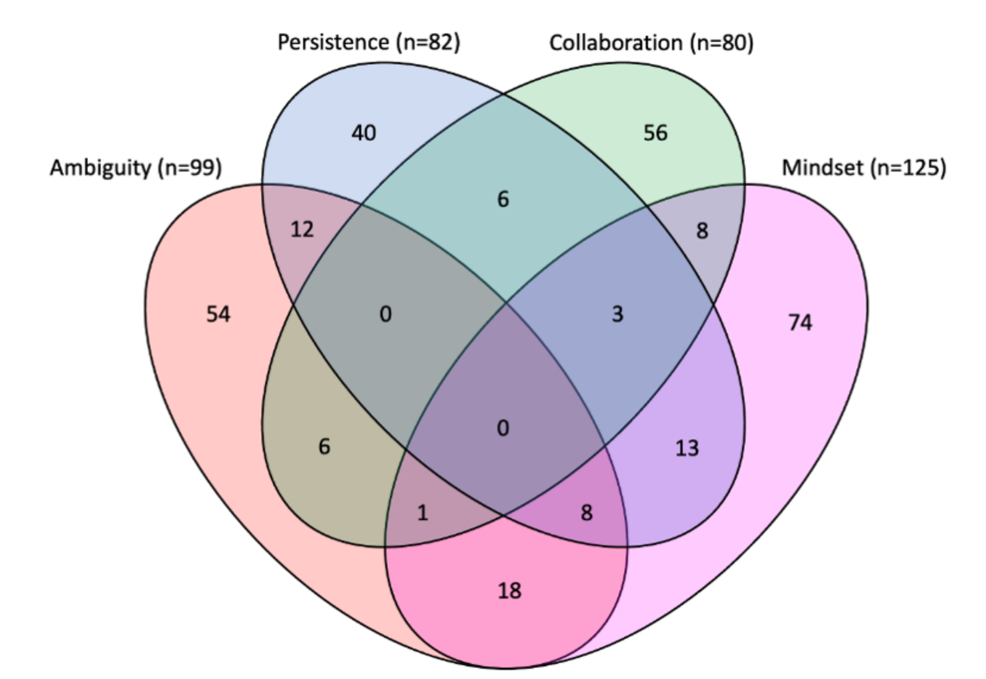

Figure 7.5: Venn diagram showing the number of coded excerpts in total that overlapped between mindset and each of the three dispositions, including overlaps between the dispositions themselves.

	Growth Mindset	**Fixed Mindset**	**Both Growth and Fixed**
High Dispositions	26	1	0
Developing Dispositions	1	20	0
Both High and Developing	0	2	0

Table 7.10: The way mindset overlapped with dispositions for excerpts in which we coded both.

7.8 Discussion

In this study, we asked two research questions: (1) How do CT dispositions apply to the context of a computation-integrated high school physics class? (2) How are CT dispositions connected to mindset in the context of a computation-integrated high school physics class?

To answer the primary research question, we coded the in-class and interview data for Otto, Blaine, and Ed, who represented a wide range views on the dispositions spectrum. We coded their data using Pérez's framework (summarized in Table 7.8), looking at their tolerance for ambiguity, persistence, and willingness to collaborate. Pérez postulated that these three dispositions were needed to promote computational thinking practices in the classroom [1]. While originally developed in a math context with a cohort of teachers, we were able to apply the CT dispositions framework to our students' data in a computation-integrated physics classroom. The framework allowed us to provide a detailed profile of each student's dispositions, which shows that the framework can be extended to a context where students are learning physics through computation. Additionally, the framework allowed us to identify nuances within dispositions for each student, but it also raised further questions about the framework and about computational pedagogy.

For example, one question that came up when using the dispositions framework was, can teachers be part of a collaboration when the focus of the study is on students? This is a new question since the framework itself was theorized in the context of a workshop series for teachers with no students involved. For example, in our data, Otto often received help from Mr. Buford in class and described these interactions in his interview. In both data sources, we coded for collaboration whenever Otto's statements and actions aligned with some of inclinations, sensitivities, and abilities of collaborating, even though he was just talking with the teacher. This is a small but possibly important point that calls for clarification in the dispositions framework when applied to the classroom. In the dispositions framework, the definition for collaboration is, "a tendency to coordinate effort and negotiate meaning with peers to accomplish a shared goal" (page 449) [1], with "peers" defined as potential collaborators. This would seem to exclude teachers from being potential collaborators.

However, we would argue that this might be dependent on the individual's perspective on the teacher and the role that the teacher plays in the classroom, rather than a blanket rule that teachers cannot be collaborators. For example, if an instructor is asking the student guiding questions, does the student not participate in the creation of the solution/answer as much as the teacher? The perspective around this point becomes more complicated in a classroom with an array of power dynamics (e.g., undergraduate learning assistants, teaching assistants, and faculty) all combined together.

From our disposition analysis, we also saw alignment of dispositions across data sources with a couple exceptions, which has implications for computational pedagogy. When looking at the data, students demonstrated similar levels of each disposition across their interview and in-class data for the most part, which suggests that the same dispositions could be observed in class or ascertained by talking with a student about their perspective on the computational activities. From a practice perspective, this might highlight multiple paths forward for operationalizing the identification of dispositions as a teaching tool. Dispositions being identifiable within in-class interactions means that teachers might be able to recognize students with developing dispositions and intervene to promote a trajectory towards higher dispositions. Alternatively, identifying dispositions in the way students answered interview questions indicates that we could develop pre surveys or reflective assessments that allow both the identification of dispositions before instruction begins and assessment of changes in dispositions over time. However, we found that there were a couple of exceptions to this alignment between data sets and that there can be nuance within a single disposition that might not be apparent from one data source alone.

For example, most of Otto's statements related to ambiguity came from the interview rather than the in-class data (over 70 percent). A possible explanation is that in the interview, Otto had many opportunities to explain how he viewed problems and how he liked to explore different features of them. On the other hand, in the in-class data, we were only able to say that he was displaying a tolerance for ambiguity when he talked about what he did and didn't know about the problem. This trend also held for Beck's data and Ed's data, where each had over 70 percent of their ambiguity codes come from their interview. This implies that ambiguity might be better assessed via reflective surveys and essays rather than relying on pure observation within the confines of the classroom.

An extreme version of the misalignment between data sources is Beck's collaboration codes, as seen in Appendix A: only two of his interview statements were coded for collaboration, whereas we coded his in-class data for collaboration 18 times. This didn't happen to any of our other participants (except to a lesser degree: Ed had 9 out of 32 collaboration codes come from her interview). Ultimately, this could come from the fact that the dispositions framework focuses on collaboration via the input and insights one *gains* from peer interactions, rather than the input *into* peer interactions. From our observations, Beck tends to give help far more often than he *gets* help. This is reflected in the data in that 15 out of his 18 collaborative codes were from two key abilities: Articulating or justifying the benefits of a particular approach, and clarifying, questioning, or negotiating the group's understanding and/or course of action. Beck's case demonstrates a stratification within the collaboration framework between those two key abilities and the rest of the collaborative codes in Table 7.1.

In addition to these structural discrepancies, we also saw some differences for some of the students between what they said in their interviews with regard to a disposition and how they enacted that disposition in the classroom. For example, what Ed says to Mr. Buford in regard to her persistence in Ed.In-class.4 is drastically different than what we observed. We analyzed this excerpt because it showed Ed telling the teacher essentially that she hardly persisted at all during the class period, yet we saw throughout the in-class data that she had a high disposition for persistence. This suggests Ed provided a harsher account (by the standards of CT dispositions) of her behavior than we observed during the class period and indicates that some students may understate their CT dispositions when describing their own behavior. Ed's discrepancy between what she said and what she did could be due to any number of reasons. For example, Ed may take her need to persist as a sign that she is making many mistakes or that computation does not come easy for her. Alternatively, she may think that Mr. Buford values the right answer (which she did get) over her ability persist. Any of these reasons would prevent her from seeing persistence as a strong positive attribute for computation, despite the positive framing of persistence in the CT dispositions framework.

A parallel to Ed's persistence is her disposition for tolerating ambiguity. Though she had mixed results for this disposition (ten high, nine developing), all nine developing codes came from her interview. She described computational activities as if the ambiguity in them was usually intolerable, but when we observed her behavior in class, she embraced the ambiguity in the computational activity. This is another instance where students can sometimes represent a different disposition depending on the context. For Ed, some explanations could be: she doesn't like the ambiguity but knows how to navigate it in class, she portrays her disposition for tolerating ambiguity more modestly when talking about it with the researcher, or she perceives her in-class performance with an accentuation on the times when she is less tolerant of ambiguity. Ed's complex relationship with the dispositions offers a word of caution to practitioners and researchers, namely that one source of data (be it in class observations, interviews, reflections, surveys, etc.) may not tell the whole story. How Ed viewed herself and what we observed were at times drastically different, yet no one data source in this case is "correct." Both how Ed feels and how she acts are equally valid, with both data sources offering a more robust view of Ed's dispositions than either one could provide individually.

Ed also gave a unique description for her collaboration, which raises another question about applying the CT dispositions framework to the classroom context. In Ed.Interview.5, she told us about the "leeching" interaction, where there was sometimes some explanation happening but no co-creation of meaning. When she shared answers with her peers, nobody could ever fully explain the solution being shared. In the current dispositions framework, a disposition for a "developing" willingness to collaborate is described as, "the learner may see others merely as a 'means to an end' rather than as co-participants in a process or co-creators of meaning." In Ed's case, there seems to be a middle ground, which would be, "the learner may attempt unsuccessfully to co-participate in the learning process."

Another mid-level code suggested by our data comes from how Beck viewed ambiguity in his interview. Although he can easily handle ambiguity, Beck likes when there is an equation to guide the process, as we discuss in Appendix A. This is a source of comfort for Beck, and perhaps there needs to be a place on the dispositional spectrum for students who have maybe not embraced the value that can be found in ambiguous problems but still demonstrate a high tolerance for ambiguous problems. This is different from Ed's description of ambiguity because she articulated an intolerance for ambiguity and then embraced it in class, whereas Beck simply articulated a preference for less ambiguity, which was still consistent with his actions of navigating the ambiguity in class well. Adding a mid-level description to the framework, such as this "attempted co-participation" code or the "preference for clarity", would allow for more nuance in describing where students may be on the dispositions spectrum and what may aid their trajectory toward higher dispositions. Further work would need to study if these new categories of codes are valid for other students and if other mid-level codes exist.

An interesting corollary is that Beck's ability to strip away the ambiguity from computational problems could indicate that if you reach a certain level of ability with the computation, you may start to perceive less ambiguity in the computational activities. Beck's preference for clarity may be driven by Beck's ability to address and handle ambiguity and derive clarity from it. This points to the potential value of "hidden curriculum" [208] as well—if teachers communicate why it is not only alright but a good thing to tackle ambiguous problems, then it can facilitate students to move into a higher level of tolerance where the student has an "awareness that engaging in uncertain situations can lead to growth" [1].

Beyond the need for mid-level codes, we also saw some brief indications that students may hold different dispositions in different contexts. For example, Otto said he preferred to work solo in his calculus class because he was highly skilled at calculus. His extra strength in calculus would indicate that his peers have even more to gain from his help than they would in physics, yet he is more reluctant to collaborate in his calculus class. This may imply that some students are good collaborators *only* when they benefit from the collaboration, which would indicate that student may be less likely to collaborate (like Otto says he is in calculus) if they become better at working through and understanding the material. Otto's comments put an asterisk on his high dispositions for collaborating. It could mean that Otto may switch approaches/beliefs about collaboration depending on the context of the activity (calculus vs physics). For example, the main contextual factor for Otto seems to be that he never needs help in calculus because he does so well in the class by himself, whereas for physics he often runs into roadblocks, which may predispose him to seeing the value of collaboration in the context of his physics class. Alternatively, the messaging in his physics class may better promote collaboration as a tool over his calculus class. We did not actually see Otto progress or switch his beliefs in our data in part because that was not the design of the study. Our data represented a snapshot of dispositions rather than a development over a period of time or a contrast between contexts; however, this could be a focus of future work on computational dispositions.

Another avenue for future work could investigate the role of the teacher in promoting dispositions. In our data, we found that the teacher's role of building classroom norms relates to the dispositions that showed up in the data. For instance, we learned of the class norm of "helping people" in Otto.Interview.5, which is something that Otto has come to expect in Mr. Buford's class after only two months into the academic year. We coded Otto's acceptance of this as a high willingness to collaborate, which indicates that there are actions instructors can take to support students in developing dispositions, such as: making resources available and accessible [209], being proactive with facilitating collaboration [209, 63], scaffolding curriculum to many opportunities for accomplishment [176], acknowledging the normal computational experiences of frustration and partial completeness [92, 179], and making the material relevant to students [210].

We summarized our dispositions analysis with Table 7.8, which pointed out how the inclinations, sensitivities, and abilities of the three dispositions were distributed among the data sources. Some key points could prove useful to practitioners and researchers. We found that tolerance for ambiguity was much more prevalent in the interview comments than the in-class behavior, which indicates that teachers wishing to assess tolerance for ambiguity may find better results by assigning a reflective essay (or something that somewhat mirrors the interview prompts) to students than trying to observe it directly. We also found that abilities for collaboration overwhelmingly showed up in the in-class data, which means that a teacher wishing to observe collaborative ability could do so by simply attending to what students do in class, as long as students are given opportunities to collaborate in the first place.

To answer the secondary research question, we also coded our data for mindset, drawing connections between the mindset and dispositions frameworks. When it came to mindset, we found that there were several examples of times when students expressed mindset and dispositions at the same time and several examples of times when they expressed mindset without dispositions. Persistence and ambiguity codes were on average twice as likely to align with mindset than collaboration was (shown in the overlap in Figure 7.5). Altogether, we take this to mean that students sometimes tell us about their dispositions and about their mindset with the same action or utterance. This doesn't mean that a student's mindset is a combination of their dispositions (or vice versa) because we saw many instances of no overlap, indicating mindset involves non-dispositional factors as well. By the same token, CT dispositions involve factors unrelated to mindset. However, it does mean that the constructs often coexist, and students can indicate both their dispositions and their mindset at the same time.

In analyzing for mindset, The difference between collaboration and the other dispositions (in that collaboration was less likely to co-exist with mindset) could be explained by the design of the research study and the development of the theoretical framework. To explain, collaboration was the only disposition not explicitly required in Mr. Buford's computation activities (see Section 7.5), though it was still encouraged through messaging and the structure of the classroom. Also, collaboration was the only disposition for which Pérez [1] did not explicitly cite mindset literature when developing the CT dispositions framework (see Section 7.3). These factors could explain why we saw less of an overlap between collaboration and mindset in our data.

In analyzing for mindset, we found several interesting occurrences in our data that have implications for using mindset in computational contexts and for how mindset relates to the CT dispositions framework. For example, we saw that Ed flip-flopped between fixed and growth mindset in the

Ed.Interview.Mindset quote. We related this flip-flop to an aspect of how Ed expressed her dispositions: she often reported a more developing disposition in her interview and then behaved in a way more aligned with high dispositions in class. The fluidity in Ed's disposition and mindset reminds us that both constructs are intended to be interpreted as a spectrum and that our positioning of Beck, Blaine, and Otto at the far ends of each spectrum is not meant to be an assertion of an absolute position but rather illustrative of their position based on Pérez's framework. For Ed it might also be indicative of the fact that she does not belong on the end of either spectrum and may be in a development process with both her dispositions and mindset. This inconsistency highlights two concerns when trying to utilize dispositions in one's teaching practice. The first is that when operationalizing, a teacher should remember that neither dispositions nor mindset should not be construed as being a dichotomy for a particular student. The second is reiterating the point that different data sources can provide different insights into a student's disposition and mindset. This should be considered when trying to ascertain a student's disposition or mindset and suggests that a combination of approaches (observations/surveys/reflective essays) might be needed to get an insight into a particular student. Moreover, Ed's case and her fluidity between fixed and growth mindsets and developing and high dispositions further strengthens the argument that there is a relationship between the two constructs.

Another aspect of the relationship between dispositions and mindset is that fixed mindset tends to correspond with developing dispositions, while growth mindset tends to correspond with high dispositions. As we mentioned earlier, this alignment held for 47 out of the 51 excerpts that were coded for both constructs. This suggests that when mindset and dispositions coexist in a student's action or statement, they are strongly correlated. It remains open whether there is any causation in this relationship, but given the widespread application of mindset interventions [124, 125, 126, 127, 128], we recommend for researchers to measure shifts in dispositions in these settings in order to ascertain whether improving mindset also leads to improvements in dispositions.

Despite the high alignment between mindset and dispositions, there were a few cases of non-alignment, meaning fixed mindset and high dispositions in the same excerpt, or growth mindset and developing dispositions. These instances are outline in Table 7.10. We argue that examining the times when there is misalignment can provide further insight into the relationship between the two constructs. Focusing on when mindset and dispositions anti-align, we describe two of the four non-aligned excerpts (the remaining two only PARTIALLY anti-aligned, having a mix of developing and high codes, as seen in the bottom row of Table 7.10). The two completely anti-aligned excerpts came from Blaine's data. In one excerpt, Blaine explained how he could learn computation from a coding for dummies book if he wanted to, which we coded for growth mindset (given his stated belief that he could grow his computational skills) and developing collaboration (given his rejection of the hypothetical opportunity to learn by working with peers, instead opting to use the coding for dummies book in this scenario). In another excerpt, he copied and pasted a past project's code into his GlowScript window (right before Blaine.In-class.2). We coded this for fixed mindset (given his avoidance of thinking about what he was copying) and high persistence (given his pursuit of a resource that in principle could help his efforts pay off, even though he wasn't using the resource, or copied code, effectively in the moment). What made these excerpts special was that they represented moments where Blaine expressed an idea or did something to advance his computational skill or progress in the computational activity, but that idea or action was not aligned with growth mindset or high dispositions in some way. In the case of the coding for dummies book, Blaine ignored opportunities to learn through collaboration. In the code-copying case, Blaine ignored opportunities to think for himself. Though the excerpts represent earnest attempts to advance in the activity or improve his skill, dispositions and mindset tell us that those attempts will not be productive in a realm where CT is needed (like Mr. Buford's class). Interestingly, this only happened twice in our data, but these examples point to the importance of fostering both high dispositions AND growth mindset in physics students, because they aren't guaranteed to go together all the time.

We focused in part on Blaine.In-class.2, where he reacted negatively to an error message and then avoided engaging with it by searching for sample code online. We coded this excerpt for fixed mindset, yet there were some common computational experiences in what Blaine did: encountering an error and searching for someone else's code online. These experiences pointed to a fixed mindset because of how Blaine reacted to the error and the reason he searched for sample code. This points to an opportunity to study mindset in computational settings, because there are many common experiences when programming, such as dealing with errors and google-searching for answers, but mindset entangles with the way a student responds to and/or brings about such experiences.

We should note, though, that copying code—or reusing and remixing code as it is often referred to in CT terms [199]—is an accepted and legitimate strategy to creating computational models. The commonality of this practice makes it an odd choice to be coded for fixed as opposed to growth mindset. For example, in the Blaine.In-class.2 quote, Blaine reacted negatively to an error message and then avoided engaging with it by searching for sample code online. We coded this excerpt for fixed mindset, yet there were some common computational experiences in what Blaine did: encountering an error and searching for someone else's code online. However, these experiences pointed to a fixed mindset because of how Blaine reacted to the error and the reason he searched for sample code. Blaine is taking a very surface approach to code copying as he is essentially looking for a solution to the problem as opposed to looking for code that will need to be interpreted and adapted for the model. This points to an opportunity to study mindset in computational settings, because there are many common experiences when programming, such as dealing with errors and google-searching for answers, but mindset entangles with the way a student responds to and/or brings about such experiences.

Though we have not been able to show conclusively that mindset and dispositions are tied together causally or whether they develop together, we were able to show that they are correlated strongly in instances when they both get expressed. Given that the origin of persistence and tolerance for ambiguity in the Pérez paper [1] came in part from mindset literature, a possible outcome of this study could have been a demonstration of dispositions being a contextualized version of mindset for environments that emphasize computational thinking. However, our results demonstrate that the constructs of disposition and mindset are related and yet different. This does imply that mindset interventions [124, 125, 126, 127, 128] that have been applied in other contexts could be adapted and used in computationally integrated physics classrooms. Beyond that, we would expect mindset interventions to have some impact on CT dispositions, but the amount of impact or ways in which that impact will manifest are unclear at this point. We highlight again our suggestion to measure dispositions in settings where mindset is also developing or where mindset interventions are taking place. More information about the relationship between dispositions and mindset could lead to proven methods for improving students' CT dispositions.

As we discuss the ramifications of the CT dispositions and mindset frameworks in Mr. Buford's class, we note that this is just one setting where this framework could be applied. As Pérez said, "the usability of the framework [increases] through examples of classroom behaviors that may accompany developing or higher levels of a given disposition" (page 442) [1]. We have provided one case with a handful of examples, but other settings with other computational integrations will provide different perspectives and nuances to using this framework. Our study provides evidence of the applicability of the dispositions framework beyond the theoretical construct that Pérez constructed. We encourage future studies in the context of physics classrooms to continue to build on this framework and account for more than just CT practices when examining computation in the classroom.

Another avenue for future work is the integration of studying CT dispositions and practices in the same setting. As we reviewed earlier, there are many examples of research focusing on CT practices [40, 133, 66, 196, 197]. It would be interesting to see how dispositions and CT practices coexist in the same setting so that the impact and importance of CT dispositions can be articulated alongside and intertwined with the impact and importance of CT practices, since these are the two sides of ISTE and CSTA's definition of CT [132].

We conclude by returning to the main outcome of this work and the answer to our primary research question—CT dispositions can be extended and applied to the setting of Mr. Buford's physics class using a research design that centers the perspectives of students. Though we had many recommendations and questions earlier in this section for applying the framework to physics students, we can say confidently that the framework is flexible to different contexts. Furthermore, it showed some strong correlation with mindset theory for instances when both constructs could describe what a student expressed. The relationship between dispositions and mindset shows promise for future work and for the robustness of the CT dispositions theory. It is our hope that student perspectives will continue to be used to ascertain both the effectiveness of computational integrations like Mr. Buford's and the applicability of learning theories like CT dispositions.

7.9 Acknowledgments

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CHAPTER 8

DISCUSSION

In this dissertation, I have explored the use of students' perspectives in curriculum development and applied the idea of leveraging students' perspectives in a computation-integrated physics context. In the first three chapters, I laid the groundwork for the research studies that followed and demonstrated the utility of qualitative case study for achieving the goals that I outlined. In Chapters 4 and 5, I showed how the perspectives of LAs in an introductory physics course can function as voices in curricular decision-making, showing how theoretical frameworks and attention to context can give structure and meaning to students' perspectives in research. In Chapter 6, I provided a catalog of student-perceived challenges in a computation-integrated physics course and laid a foundation for more focused studies by exploring how affect-related constructs (self-efficacy, mindset, and self-concept) related to students' experiences. In Chapter 7, I built on the foundation from the previous chapter by applying the theories of mindset and Computational Thinking (CT) dispositions to see how they interact in a computation-integrated physics context, in effect extending the theory of CT disposition and highlighting the potential for mindset to function as a window into how students enact CT in a computation-integrated STEM context. Overall, this dissertation serves to amplify the perspectives of students in a new and increasingly more widespread context—computation-integrated physics—where there is a notable opportunity to infuse students' perspectives into curriculum development widely.

In more detail, we set up Chapters 4 and 5 by showing that student perspectives are consulted broadly in physics education, but rarely have students' voices had an explicit part in curricular and pedagogical decision-making in the way that more recent efforts have shown [29, 31], in which students' perspectives factor directly into curricular and pedagogical decision-making. My research showcased in Chapters 4 and 5 characterized a student-partnership in an introductory physics course, and it showed that Students as Partners was applicable to learning assistants (LAs) in a course with a Communities of Practice design. I also learned by doing this research the importance of paying attention to theoretical perspectives and contextual factors when listening to students' perspectives. There is potential to build on this work in several ways. First, the specific course (P-Cubed) could be improved by further reifying the contributions of LAs into the curriculum. Researchers could re-envision other LA programs as student-partnerships, especially those designed with a leaning towards fostering a community of practice. LAs' voices need to be promoted and made louder as they are afforded unique perspectives on the classrooms that they teach in as they often experience it both as a student and a teacher. The LAs in P-Cubed also return for multiple semesters and often garner more experience teaching the class than the TAs and faculty empowered to teach the class. Developing a community and procedures that value their experiences and provide venues for their voice is essential for needed continued evaluation of our classrooms. There is also an opportunity to investigate other P-Cubed LA practices (other than the formative feedback) to see how else to leverage LAs' perspectives and incorporate them into the class's design.

Building on my work in Chapters 4 and 5, I applied what I learned about how to listen to students productively to the context of computation-integrated physics. In designing and carrying out the study showcased in Chapter 6, I identified and addressed a significant gap: computation-integrated physics is a curricular setting where students' perspectives have not been incorporated. Given how recent computation-integrated initiatives are in education, research on students' perspectives in computation-integrated physics is surface-level and scarce [33, 72, 71, 70, 73, 74]. In response, I designed and carried out a case study that explored students' difficulties in their computation-integrated physics classroom. In terms of findings applicable to the curriculum, the students in Mr. Buford's class struggled with several affect-related challenges: Stress/Frustration, Strain on Physics Knowledge, Unbelonging and Stereotypes, Responses to Setbacks, Interpreting Code, and Contextual Challenges.. For curriculum developers, my findings highlight the importance of communicating expectations when introducing computational activities, designing activities with some easily attained successes in them, relating to students' computational struggles, and discussing the positive long-term impacts of learning computation. I also connected the students' perspectives to the educational theories of mindset, self-concept, and self-efficacy. The connection to theories was an emergent part of the analysis, demonstrating how theoretical lenses can show up and function in a computation-integrated physics setting. My research in Chapter 6 calls for exploratory research in other computation-integrated school contexts, especially those with different implementations from Mr. Buford's and with different curricular constraints than the AP curriculum. My work also found initial connections to affect-based constructs; however, more work needs to be done to explore how these constructs manifest in the computation-integrated physics context. I would recommend such studies to apply theoretical lenses onto students' perspectives, whether new lenses or using mindset, self-concept, and/or self-efficacy in more depth. Ultimately, Chapter 6 can serve as a jumping-off point for any study that examines students' perspectives in computation-integrated physics.

Chapter 7 directly builds on the exploratory work of Chapter 6. This chapter was focused on adapting a theoretical construct that related to one of the barriers that emerged from students' perspectives in Chapter 6 to the context of computation-integrated physics curricula. In this chapter, I outlined a study that showed more in-depth how theory can enhance descriptions of what students experience in computation-integrated physics, highlighting areas with the potential to instigate meaningful and productive curricular change. In Chapter 7, I extended the utility of the CT dispositions framework by showing how it applied in a new setting, and I investigated the relationship between CT dispositions and mindset. I also demonstrated how different data sources in Mr. Buford's class provided different insights into students' CT dispositions. This finding in particular could help teachers and researchers select appropriate methods for examining CT dispositions in computation-integrated STEM settings. Future work could include measuring CT dispositions during mindset interventions as a way of further characterizing the relationship between the constructs. CT dispositions could also be explored in other contexts (even other computation-integrated STEM contexts) to further strengthen the framework. Furthermore, there is an opportunity to study how CT dispositions and practices come together in a computation-integrated STEM context. Lastly, while we focused on the construct of mindset, there are other affect-based constructs that could be applied in meaningful ways in this context (as shown in

Chapter 6). Future work could also include applying these other theories to students' perspectives in computation-integrated STEM. In a sense, Chapter 7 serves as precedent for such further studies, as we have already pointed out the gap in computation-integrated STEM literature and demonstrated that research can be carried out to address it.

The limitations of this work comprise the limitations of qualitative case study combined with the limitations of doing research in a somewhat unexplored context. I am unable to make claims about causality [47]. Though I have recommended pedagogical strategies and certain features of curricular implementation, I cannot guarantee their effectiveness in any context. Anyone who wishes to use this research and its recommendations needs to build an awareness of their own context in order to come to reasonable conclusions about what they can expect based on how their context relates to the cases I presented in this dissertation. This research is also limited in the sense that computation-integrated physics remains a barely explored area. It is difficult to ascertain how my cases relate to others due to the scarcity of student-centered research in this area. Mr. Buford's implementation of integrating computation could bear hardly any resemblance to many other implementations, which would limit the immediate practicality of my findings. It is hard to know without more research.

As computation continues to be integrated into STEM classrooms in schools around the world, students' perspectives continue to be an excellent (but underutilized) resource for curriculum designers and researchers. There are opportunities to incorporate students' perspectives into curriculum with more depth than ever before catalogued in research [28]. There are opportunities to leverage student input in computation-integrated contexts, which are growing in number and ever changing as research calls for it [33]. Now is the perfect time, as computation spreads widely, to design research and curriculum that centers students' perspectives.

APPENDICES

APPENDIX A

BECK RESULTS

A.1 Beck Disposition Profile

Beck's statements and actions demonstrated high levels across all dispositions. In Table A.1, we show the codes for his interview and in-class data. He had completely high codes for persistence and collaboration, which indicates the highest levels of these two dispositions. We only coded for collaboration in Beck's interview twice. For tolerance for ambiguity, he had a handful of developing codes in his interview but none from his in-class data. We discuss where this discrepancy comes from below.

A.1.1 Ambiguity

Beck tended to have a high tolerance for ambiguity, especially when during the in-class activities. He embraced ambiguity when it presented itself, though he didn't seek it out on his own; he preferred clarity and concreteness. In the excerpt below, he contrasts different school subjects based on the "interpretation" of what he has to do in them.

Beck.Interview.1:

	Tolerance for Ambiguity	**Persistence on Difficult Problems**	**Willingness to Collaborate with Others**
Beck Interview	18 high 9 developing	11 high 0 developing	2 high 0 developing
Beck In-class	11 high 0 developing	14 high 0 developing	18 high 0 developing
Beck Total	**29 high 9 developing**	**25 high 0 developing**	**20 high 0 developing**

Table A.1: Coded instances of dispositions for Beck, separated by data source and tallied.

INT You mentioned some subjects you don't like, English, history, how do those compare with physics and math?

BECK It's mostly the thing I was talking about, a lot of it is interpretations stuff, things like- poetry is one of my least favorite things. You have to interpret it and **there's so many different ways to interpret it**, and you're like, yes, that's correct. But now you have to support your answer with everything. And **I like something that has a clear answer.** I've come to realize that the physics conceptual things, they obviously- they do have a clear answer. But at the beginning, since I didn't understand, **I wasn't able to figure out what the clear answer was. So I didn't really like it, the conceptual stuff that much.** But now, I mean I understand most of the things pretty well so I can see, 'Oh yeah,' there is one clear answer. **Even if I don't get it at first, there is something, that it has to be correct**...

INT So I definitely have some things I want to follow up on... You mentioned earlier, when you are able to explain a physics concept, that's how you know that you really know it and you can explain it to other people. Is that in some way explaining your interpretation of the problem?

BECK A little bit, but yeah, sort of I guess. But what I mean is **there's an equation**. For example, the thing I was doing the other day was refraction, when there's a ray of light that goes into a substance, like a glass. If the speed of light in them is different than it'll change direction and it'll bend. That sort of stuff is, I feel like it's... There is of course some interpretation, but **I feel like it's more specific.**

The first subject he brings up is poetry, where "there's so many different ways to interpret it." This ambiguity doesn't sit right with Beck, who prefers "something that has a clear answer," indicating a preference for a single solution (though not an inability to recognize when there are multiple solutions). He goes on to describe his initial physics experience, when he "wasn't able to figure out what the clear answer was." He said this caused him to "not like the conceptual stuff," indicating that he had a disinterest in exploring unfamiliar situations. He acknowledged that he has since grown: "Even if I don't get it at first, there is something, that it has to be correct." His growth came from warming up to the murky conceptual physics problems, in effect exploring an unfamiliar situation.

We noticed in his response to the follow-up question that he is focused on the presence of "an equation" when working through physics concepts. He goes on to describe the concept of refraction, and qualifies it with, "I feel like it's more specific." This focus on the "specific" nature of physics concepts and the related equations points again to a preference for anchoring the physics problem in a more concrete, rigid idea. The discrepancy between Beck's ability to handle ambiguity yet his preference for more straightforward problems indicates Beck sometimes may not be seeing the value in the ambiguous problems.

Adding more nuance to Beck's views on ambiguity, he described the complexities of applying physics knowledge to computation and the benefits of interacting with a working, dynamic solution. **Beck.Interview.2**:

> BECK Well for the coding **you have to actually apply what you've learned... understand the math behind it and what's actually going on.** Because when you're coding, first of all, **you actually get to see it happen in real time**. . . And also you're able to implement the different things that you've learned and alter it slightly, and can make huge changes and things like that.

Beck's first comment about doing computation reads like an instruction: "you have to actually apply what you've learned." Later, he clarifies: "understand the math behind it and what's actually going on." This entails bringing together prior learning, digging into the underlying math, and seeing the problem for what it "actually" is. This is a reframing of the seemingly ambiguous features of the computation as an opportunity to clarify what is known about the problem. In Beck's view, this reframing is valuable: "you actually get to see it happen in real time." This achievement represents an awareness on Beck's part that engaging with the uncertain parts of computation can lead to a growing understanding of physics.

In class, Beck demonstrated a high tolerance for ambiguity in how he acted and talked with other students about the computational activity. Below, he expresses some comfort with just picking a number for his code, without regard to whether it's "correct" or not (or even whether there IS a correct answer).

Beck.In-class.1:

BRIAN Are we supposed to have like five balls?

BECK **I have four. I don't know if there's a certain number we need**

He didn't know how many "balls" (representing light particles) were required, he just picked a number. Unlike Brian, who was in search of specific guidelines, Beck seems content with choosing "four." This may seem trivial but the ability to make a choice without being worried whether it was right indicates that he is okay with the presence of multiple possible solutions and that he has accepted the variance that may result from students picking different numbers. This is just one of the handful of times in the in-class data that Beck exhibits a tendency to acknowledge multiple possible solutions.

Beck has a high tolerance for ambiguity, as indicated by the key aspects of this disposition that he displayed in the excerpts above: an interest in exploring unfamiliar situations, an accepting view of variance, an awareness that engaging with uncertain situations can lead to growth, an alertness to opportunities to clarify what is known and unknown, and a responsiveness to approaches for reframing ambiguous situations. These dispositional skills that Beck has differentiate from his interview when he articulated a *preference* for less ambiguity. We coded aspects of this preference for a disinterest in exploring unfamiliar situations, an unawareness that engaging with uncertain situations can lead to growth, and an adherence to the idea of a single solution path. Overall, this preference does not add up to an intolerance, and it certainly did not preclude Beck from exhibiting a high tolerance for ambiguity during class.

A.1.2 Persistence

Beck demonstrated high persistence in both his interview and the in-class data. When asked how he deals with stuckness in his interview, he explained a go-to strategy that demonstrated he does not give up right away.

Beck.Interview.3:

INT What do you do when you get stuck?

BECK I just try to write it out on a paper and say I would, I try to draw the thing that we're doing because a lot of it, most of it is visual for the coding. **So I try to draw the thing and see what sort of relationships I have.** Like yesterday, I drew the light and the lens, and I was like, Oh there's a triangle here. Maybe I can find the portion on the bottom, the vertical portion, and then I could do the Pythagorean theorem on it to figure it out or something. Or use trig or something.

The first tactic he takes up is "to draw the thing and see what sort of relationships I have." His interest in exploring relationships between aspects of the problem indicates that his focus is on discovering new information, even in the midst of stuckness, without guarantee of success. This also shows that Beck has an alertness to the different characteristics of the task, since he is able to derive new insight simply from sketching out its features.

We followed up later in the interview to see what other strategies Beck might turn to.

Beck.Interview.4:

INT Okay, so you're drawing it on paper. Do you ever wait for Mr. Buford to get help?

BECK I try not to. I mean **if I ever get really stuck I will just go up to him and ask him** because if I have no ideas whatsoever in my head. Like I draw it out and I just don't have any idea what to do, I'll definitely ask him, yeah. I've done that a couple of times.

At times, when Beck is really stuck, he will just go and ask Mr. Buford for help. This indicates that he has a backup plan, or safety net, for when he can't figure out how to overcome the difficulty at hand. This would constitute trying a new approach after considerable effort.

The in-class data further reflected Beck's disposition for high persistence. One feature of his workflow is that he often thinks out loud about what he is doing, which provides a window into his thought process. His think-aloud style of working through the computation shows that he is consistently trying new things and hitting snags with the code, but he always persists through them without ever giving up.

One example of his persistence was more drawn out, and it happened right at the start of class when he was searching for how to correctly use a specific function in the code.

Beck.In-class.2:

BECK °So: how do I: ^help^°

(3.5)

BECK °How do I-° Oo there we go, ^add an arrow^

(24.0)

BECK How do I- oh there we go, ^attach arrow^

The carrots ("^") indicate a cadence for reading text, which means Beck is likely reading off options in the help menu as he searches for a function he can use. He starts out with a question indicative of stuckness ("how do I"), and he cuts himself off to indicate that he has navigated to the help menu, a popular GlowScript resource in Mr. Buford's class. The same pattern happens twice again over the next 30 seconds, indicating that he is using the GlowScript documentation as a resource to help him carry out the task more effectively.

Later in class, he runs into an error message while helping Otto. Beck's willingness to try out a new approach right away further indicates his disposition for high persistence.

Beck.In-class.3 / Otto.In-class.5:

OTTO So run that and it'll just, ((pointing)) straight

BECK Let's see what happens, should do (inaudible). Straight to the right. ˆInconsistent indentation one fullˆ- **let's see, see that's why I didn't- Alright so, light- I'm just gonna**

OTTO Just retype it

BECK **ˆWhile light dot position dot x less thanˆ**, °what was it?°

OTTO Light- I mean um

BECK Focal point?

OTTO Uh, yeah. Focal point dot pos: x

BECK °Position dot x°

OTTO Hundred

BECK °Velocity one hundred°

BECK Er::, oh! Got it. Oh, colon

OTTO OH you need a colon? Ah!

BECK One hundred. Yeah, that's a thing you do need. **It should- Yeah! And <u>that</u> just travels straight to the right.** Until it gets to there

While helping Otto get a particle to move in a straight line, Beck gets an error message ("inconsistent indentation one full-"). He immediately reacts constructively to the error message and tries to fix the mistake. His reaction was to process the error message ("let's see...alright...I'm just gonna"), with his next few utterances indicating a retyping of portions of the code (e.g., "while light dot position dot x less than"). His constructive response to the error indicates his attentiveness to the opportunity to shift tactics. When his efforts yield success, he interrupts himself with a positive exclamation ("Yeah!"), indicating satisfaction at the fruits ("that just travels straight to the right") of his significant effort.

Throughout Beck's interview comments and in-class conduct, he displays a consistently high persistence on difficult problems. When examining the excerpts above, we observed several key inclinations, sensitivities, and abilities: an interest in what may be discovered even in an unsuccessful attempt, an alertness to a task's characteristics, an awareness of the satisfaction that will be felt when efforts pay off, an attentiveness to opportunities to shift tactics when needed, an ability to try a new approach after considerable effort, and a pursuit of resources that increase the effectiveness of his effort.

A.1.3 Collaboration

Additionally, Beck displayed a disposition for high willingness to collaborate, which was consistent across his interview and in-class data. Most of the collaboration that happens with Beck involves helping a peer rather than getting help, but he collaborates so often that we saw instances of both. His view towards collaboration can be exemplified in what he thinks of "explaining," shown below.

Beck.Interview.5:

> BECK If I can explain it to somebody then I usually know I understand it pretty well. Like I've explained a couple of things like that to my dad, I do that sometimes- Because teaching things usually helps you learn it even better. For me at least. **So if I can explain something to somebody else, then that's usually a sign that I know it pretty well.**

For Beck, when he explains something successfully it indicates that he understands it: "if I can explain something to somebody else, then that's usually a sign that I know it pretty well." Sometimes he even just explains stuff to his dad. This embrace of explanation indicates an ability to negotiate meaning with others.

When asked about group work, Beck acknowledged that he participates regularly:

Beck.Interview.6:

> INT Do you ever consult with your other group members at your table?

BECK Yeah. Yeah. Even with people not at my table, like there's our table and there's a table behind me too. Kind of just one big table, I'm part of both of it. **I ask people if they have any ideas, or if they're ahead of me or behind me.**

This excerpt shows that Beck believes that sometimes peers can be sources of ideas, and also it's nice to gauge where everyone is at: "I ask people if they have any ideas, or if they're ahead of me or behind me." He likes to know how others are doing during physics class. This shows his tendency to invite and value perspectives different from his own.

Examples of this idea-sharing and collaboration abounded in Beck's in-class data. Below, we show Beck's disposition for high willingness to collaborate with Otto. In the conversation, Beck helps Otto implement a while-loop in his code in order to make some particles move on-screen.

Beck.In-class.4:

OTTO We're gonna, think about that later. So, how do I make it move?

BECK Okay, so. ((laughs)) $Pretend that never happened.$ So yeah you need a while loop. So [you wanna s- you wanna set something

OTTO [Just do control z there

BECK No you wanna set s- °I'm gonna type (inaudible).° **You wanna have something d t, change in time**

OTTO Okay

BECK Point one's usually a good one. So you need a while loop. Uh:, for now **we'll just do true you can go set the condition [when you want it to stop later**

OTTO [No I like this- I have, °I have a condition that I like. I have a condition that I want to (inaudible)°

BECK Okay. Cool then. **That's a good condition**

The sequence of interaction in the excerpt begins with Otto asking for Beck's help, Beck suggesting a while loop, and then Beck showing Otto how to implement it. In the middle of the excerpt, Beck spends time explaining features of the loop ("you wanna have something d t, change in time" and "you can go set the condition when you want it to stop later"). When Beck explains the time-step ("d t"), this represents a negotiation of the approach that Beck is implementing in Otto's code. When Beck explains that the "true" condition allows Otto to set up a different stopping condition later, this is a justification of the benefits of Beck's suggestion. Otto responds to this point by saying he already has a condition in mind (though the description was inaudible). Beck responds positively ("that's a good condition"), which indicates that he values Otto's perspective on this part of the code.

We also examine an interaction that Beck had with Blaine near the beginning of class. It was when Blaine indicated that he had an issue with his code, a code that Beck had tried to help him with during a prior class period's computational activity.

Beck.In-class.5:

BLAINE It still doesn't curve

BECK I don't unde- **I don't understand what your problem is Blaine, okay?** ((turns back towards own table)) A- It literally in the end put my**<**

BECK ((turns abruptly around the other way)) **How are you doing Otto?**

Blaine's complaint ("it still doesn't curve") is met with a harsh response from Beck: "I don't understand what your problem is Blaine, okay?" Beck then begins to comment on the issue, but he cuts himself off abruptly, as indicated by the less-than symbol ("<"). Beck then checks in with Otto ("how are you doing Otto?"), indicating an alertness to the interpersonal dynamics (in this case, check-ins) that can enhance the effectiveness of interactions. This alertness could also explain his avoidance of engaging with Blaine, since Blaine is usually a source of distraction in class. The way Beck cuts himself off could mean that he was initially willing to engage but then thought it would be better to leave Blaine be. In this interpretation, Beck's awareness of interpersonal dynamics extends to both Otto AND Blaine.

Overall, Beck has a high willingness to collaborate with others and an awareness that not all interaction has to be collaborative. Though he is more often on the helping or explaining side of a collaboration, he still recognizes the value that his peers bring to the table. He tended to exhibit collaborative tendencies much more often in class than in his interview, but all the same we were able to witness his high disposition for collaboration in both data sources. In the above excerpts, Beck demonstrated a tendency to invite and value perspectives different from his own, an alertness to interpersonal dynamics that may enhance or impede effective interactions, an ability to articulate and justify the benefits of a particular approach, and an ability to clarify and negotiate a shared understanding and course of action.

Through all three CT dispositions, Beck was on the high end of the spectrum. This is especially true for persistence and collaboration, where we had coded zero times for "developing." For tolerance for ambiguity, Beck articulated a preference for clear-cut answers in his interview, but this preference didn't stop him from enacting a high tolerance for ambiguity during the computational activity.

A.2 Beck Mindset Results

Beck displayed high levels across all three dispositions. When we looked at how mindset was present in his data, both in and out of our dispositions analysis, we saw a similar story to Otto, namely that Beck had a vast majority of growth mindset codes (compared to fixed mindset) in his data.

For instance, in Beck.Interview.3, Beck described what he does upon getting stuck during computational activities. In the dispositions analysis, we focused on his strategy to draw out different pieces of the problem on paper and try to see relationships that might help him get unstuck. This was evidence for his tendencies to look for ways to discover new information and remain alert to different characteristics of the task, both indicators of high persistence. His list of tactics and emphasis on learning more about the problem also pointed to a few characteristics of a growth mindset: a view of setbacks as overcome-able, interpreting a mistake (or stuckness) as a learning opportunity, and a view of effort as the path to success.

Much like the other students, we also found mindset codes that did not overlap with the disposition codes. For example, Beck describes the benefits of computation and why he likes solving problems in this way, focusing on computation's creative possibilities and the relationship between computation and the real world, rather than its complexities and ambiguities.

Beck.Interview.Mindset:

BECK I mean GlowScript, it allows you to apply to stuff that you've learned in a way that's different from just solving a problem on paper, because **you actually get to see the result of what you've solved in real life.** I mean it's a computer, but **you get to see it actually work.** And it gives you a view of what physicists do, I suppose. Like you get a problem and **you use physics to solve the problem, then you see it actually work... I like the coding in physics because of that.**

Beck highlights a few different times the opportunities that he "gets to" have when he does computation. He "gets to see it actually work." He "gets to see the result...in real life." His framing of "getting" to have these experiences indicates that see computation as an opportunity and he wants to learn via computation. He makes this explicit at the end of the excerpt: "you use physics to solve the problem, then you see it actually work... I like the coding in physics because of that."

Finally, we see Beck in a situation where he becomes aware of a mistake in class and says what he did wrong earlier that led him to become stuck.

Beck.In-class.Mindset:

ED Maybe you could low key just like, <u>choose</u> [a focal point and say <u>goes</u> <u>towards</u> <u>focal</u> <u>point</u>=

BECK [Oh! =That's literally what I'm doing

ED $Yeah$ don't try to, be smart about it

BECK I just, **I wrote in the wrong variable is the problem**

...

BECK Here he- this is what I have ((turns laptop towards Ed, then turns laptop back to self)) Oh: no! **It keeps not working. [I keep putting while and forgetting to do anything after**

In the first comment, Beck talks back and forth with Ed, where Ed suggests the straightforward fix of making the particle go towards the focal point, and Beck says that he is already trying to do that. The interaction doesn't lead to any change, but we do get to see Beck articulate the source of the problem: "I wrote in the wrong variable is the problem." In the next comment, Beck is about to show his new animation to Ed when an error pops up, preventing the code from running. He again says the issue out loud: "I keep putting while and forgetting to do anything after." Both admissions demonstrate that Beck is aware of the exact mistake that caused him to get stuck, and he is not hesitant to say out loud to his peers what the mistake was. This indicates that is not trying to avoid or deny mistakes, and he is instead taking responsibility for his mistakes, an indicator of growth mindset (see Table II).

In Figure A.16 above, we show how Beck's excerpts were coded in overlapping and non-overlapping ways. The takeaways are not new compared to other students. Similar to Otto, Beck has a growth mindset through many parts of the data (as seen in Table IX), whether or not CT dispositions were there, too. Like others, Beck has a slight majority (10 out of 16) mindset-coded excerpts coded only for mindset and not any dispositions. Like Blaine, Beck has little overlap (in Beck's case, none) between collaboration and mindset.

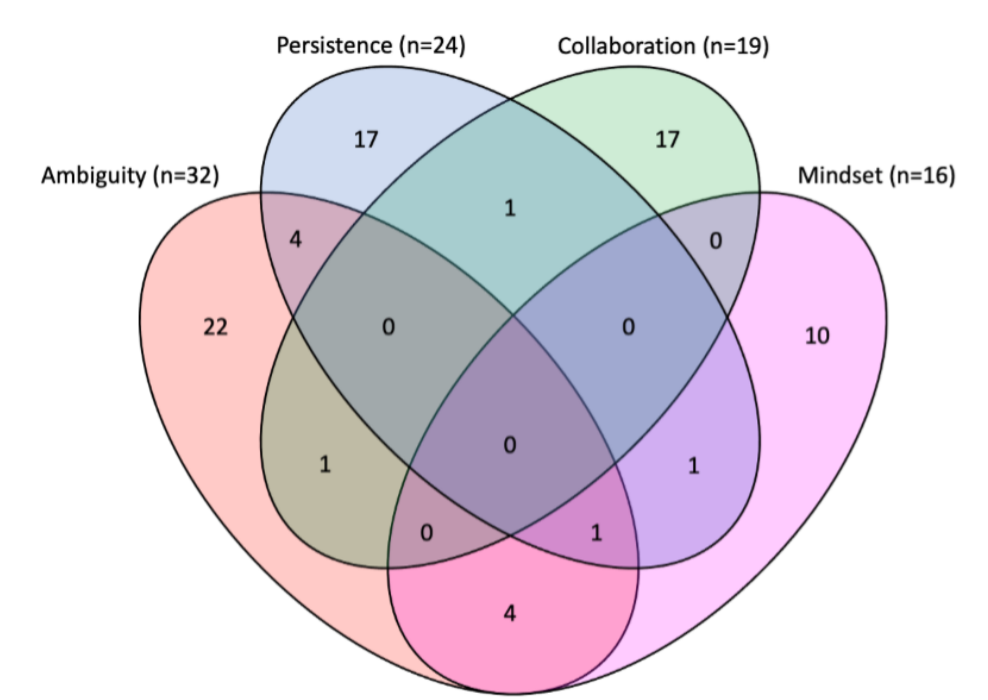

Figure A.1: Venn diagram showing the number of coded excerpts in Beck's data that overlapped between mindset and each of the three dispositions, including overlaps between the dispositions themselves.

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