COLLABORATIVE LEARNING ENVIRONMENTS IN INTRODUCTORY PHYSICS

By

Alanna Shannon Pawlak

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ABSTRACT

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Introductory physics courses are being transformed in many ways as physics education strives to better prepare students for continuing studies and the workforce. One particular transformation being adopted is the implementation of "collaborative learning environments", wherein students work together in small groups, and instructors teach by guiding the students as they solve problems, rather than disseminating information as in a traditional lecture. Collaborative learning environments are complex and rich with opportunities to study the teaching and learning of physics, and this dissertation was motivated by the need to understand how both students and instructors engage in these environments. When examining a system as complex as collaborative learning environments, it is necessary to conduct research from several perspectives. The research presented in this dissertation accomplishes this by investigating the perspectives of both instructors and a students, and by considering expanding scopes of analysis.

The first study presented investigates collaborative learning environments from the instructor perspective with a narrow scope. Through the analysis of interviews with undergraduate teaching assistants (known as learning assistants) working in a collaborative learning environment in introductory physics, it identifies the ways they approach teaching problems that require their students to model physical phenomena computationally. The results indicate varying levels of sophistication in how learning assistants perceive and utilize the computational problems in their teaching, with implications for how learning assistants are trained and supported.

The second study presented shifts from the instructor perspective to the student perspective, with a relatively narrow scope of analysis. It examines specifically how students reason conceptually in collaborative learning environments in introductory physics, and uses the construct of epistemic games, which are emergent, structured problem-solving strategies that students may be observed to employ. The results describe the identification of a new group-level epistemic game comprised of both individual and collective actions that a group of students may take when reasoning through conceptual problems.

The third and final study presented continues to focus on the student perspective, but applies the most expansive scope by considering the ways that students engage in collaborative learning environments in introductory physics that go beyond conceptual reasoning. It presents the development of a new framework for understanding student engagement with collaborative learning environments that also attends to the tone of students' interactions and the structure of their discussions. The results indicate that the framework is flexible enough to be productively applied in diverse types of collaborative learning environments, and offers instructors a practical tool to understand and develop their classrooms.

Together, the three studies presented in this dissertation provide a multifaceted view of collaborative learning environments in introductory physics courses that offers new insight into these complex environments, with practical utility for informing instructional choices and best serving students.

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Chapter 1

Introduction

A growing collection of reports and recommendations developed by federal agencies, professional scientific organizations, and other interested groups have called for an increase in the number of well-prepared STEM majors entering the workforce and higher education [1–5]. In order to achieve this, STEM disciplines have had to examine the instruction and education that they provide to their undergraduate students [6–9]. Discipline-based education research (DBER) is a field of study that has developed that is particularly well-suited to conducting the research necessary to guide and inform the changes that STEM disciplines make to their undergraduate experiences [10]. DBER researchers study the teaching and learning of a particular discipline from the perspective of being experts in that discipline and being situated in that discipline. Physics education research (PER) is one area of DBER that has developed specifically around the teaching and learning of undergraduate physics. PER has studied numerous aspects of undergraduate physics, including students' conceptual reasoning [11–30], instructional methods [19–22, 31–43], the impact of implementing reforms [19–25, 31, 44–46], student attitudes and beliefs [44–46], and issues of equity and inclusion[47–49].

From the results of studies on many of these aspects, and from knowledge taken from other fields of research, there has been an increasing push to make introductory physics courses more interactive [8, 10, 19, 50, 51]. "Interactive engagement" is not always a clearly defined term in physics education and physics education research, and can refer to things as varied as asking clicker-questions in a lecture course, conducting traditional laboratory experiments in groups, allowing students discussion time in class, and facilitating a problem-based learning course [19, 50, 52, 53]. If physics as a field is promoting interactive engagement methods as a way to improve their undergraduate education and to ultimately produce more and better-qualified graduates, then it is crucial that we understand how these methods are being implemented and the nuances of the many effects they can have on student learning and engagement. Because interactive engagement is such an all-inclusive term, it is very difficult to study it as a whole productively. Instead, it is often more useful to focus on particular forms of interactive engagement. The form of interactive engagement that I examine in this dissertation is "collaborative learning environments". For the purposes of this dissertation, these are formal physics learning environments in which there is little to no lecturing by an instructor, and instead small groups of students work together with the guidance of an instructor.

In this dissertation, I will present three studies that investigate some of the many research questions surrounding collaborative learning environments in introductory physics courses. A topic as complex as collaborative learning environments can be, and perhaps must be, studied from multiple perspectives in order to develop a robust understanding of it. One way to capture different perspectives is to consider varying scopes; that is, attending to different scales of focus in one's research. For example, using a narrow scope to focus specifically on students' use of equations in groups versus using a more expansive scope to consider student engagement in collaborative learning environments holistically when conducting one's analysis. Another way to capture different perspectives is to study the experiences of people inhabiting different roles. For example, observing the behavior of students versus the behavior of instructors. The studies I will present here use both of these methods of capturing multiple perspectives in order to examine collaborative physics learning environments in a multifaceted way. Starting from a very narrow scope and broadening to the largest, and starting from the instructor perspective then shifting to the student perspective, these studies together present results that provide a rich understanding of these learning environments.

The first study, presented in Chapter 3, is "Learning Assistant Approaches to Teaching Computational Problems in a Problem-Based Learning Course". It presents a phenomenographic analysis [54, 55] of interviews with undergraduate learning assistants regarding their experiences teaching computational problems in a problem-based physics course. This study takes place at narrowest scope, probing the learning assistants' experiences teaching a specific type of problem, and it examines the unique role that instructors have through the experiences of individual learning assistants. The second study, presented in Chapter 4, shifts from the instructor perspective to the broader and more varied student perspective, but still maintains a relatively narrow scope by focusing on students' conceptual reasoning specifically. Titled "Identification of a Shared Answer-Making Epistemic Game in a Group Context", it describes a particular method of problem-solving that groups of students were observed to engage in when working on conceptual physics problems in a collaborative laboratory class session [56]. The third study, presented in Chapter 5, has the most expansive scope. The "Development of a Modes of Collaboration Framework" presents a framework for describing the distinct ways in which groups of students interact when working in collaborative physics learning environments [57]. Like Chapter 4, it considers the student perspective, but broadens its scope to consider aspects of students' engagement with collaborative learning environments beyond their conceptual reasoning, such as their social interactions and the structure of their discussions. As a result of studying collaborative physics learning environments from these three increasing scopes, and from the perspective of both students and instructors, I will present in this dissertation a rich picture of this complex topic.

Before the presentation of the aforementioned studies, Chapter 2 will provide a broad overview of collaborative learning environments, research on collaborative learning environments, and the collaborative physics learning environments at Michigan State University, where the studies in Chapters 3, 4, and 5 took place. After the presentation of the studies, Chapter 6 will synthesize the results of these studies and provide some closing thoughts. We will proceed now to an overview of collaborative learning environments.

Chapter 2

Background

2.1 Introduction

Physics education research, discipline based education research, and education research broadly have studied collaborative learning from many perspectives and with many methods over the past decades [50, 58–61]. Having such a multitude of approaches is essential to studying the complex system that collaborative learning is. To gain a deep understanding of such a multifaceted phenomenon, researchers must investigate it with varying scopes and from the diverse perspectives of different participants. This chapter will give an overview of some ways the education research community has done this. First, a review of what "collaborative learning" can refer to will be provided, in order to give an understanding of the landscape of these contexts. Next, a more detailed discussion of research focused specifically on instructor perspectives on collaborative learning will be given. Then, shifting to the student perspective, work focused specifically on student reasoning in collaborative learning environments will be discussed. Finally, broadening to the most expansive focus, a review of research on student experiences beyond conceptual reasoning in collaborative learning environments will be presented. Like the literature reviewed in this chapter, the three novel studies presented in Chapters 3 through 5 of this dissertation examine collaborative learning from both the instructor and student perspective, and from a narrow focus to a broad focus.

The review in this chapter provides the basis of the novel research in this dissertation, with a more detailed discussion of the particular literature relevant to each study and its methods appearing in each chapter. This chapter will also provide background on the context in which these studies were carried out, physics courses at Michigan State University.

2.2 What is collaborative learning?

Before examining the different ways in which collaborative learning environments in physics have been studied, it is worth unpacking what "collaborative learning" means. Like "interactive engagement" and "active learning", there is no single agreed upon definition regarding what constitutes collaborative learning [19, 50–53], and correspondingly, it can take on vastly different forms. Here we will review several formats of collaborative learning and various collaborative activities that have been implemented in physics education, in order to come to an understanding of the landscape of collaborative learning.

2.2.1 Formats of collaborative learning

Perhaps the most common form of collaborative learning in university physics courses is the interactive lecture. Like a traditional lecture, these environments tend to have a primary faculty instructor positioned at the front of the room giving lectures, but also incorporate pauses for small group discussions or demonstrations [20, 33–36]. Some particularly common forms of interactive lectures include the use of Clicker questions and discussions [35] and Peer Instruction [20, 36]. Clicker questions are typically brief, multiple-choice questions given in lecture, which students respond to in real time using an electronic remote. In the collaborative implementation of Clicker questions, students are given the opportunity to discuss their thoughts and answers with their neighbors [35]. Peer Instruction is a well defined implementation of Clicker-style questions, wherein students are asked questions after each portion of new material, which they respond to individually, then discuss with their neighbors, then respond to again. This type of lecture that incorporates time for student discussions is just one form of collaborative learning, however.

Another well established form of collaborative learning in physics is seen in laboratory courses. Laboratory exercises are often done in pairs or small groups, in which students are expected to work together to carry out and analyze an experiment [19, 34, 62]. Even within this context, however, the appearance of collaborative learning can vary. In some laboratory courses, students may work relatively independently even within their pairs, while in a more intentionally facilitated courses, they may be explicitly encouraged to interact in particular ways [34, 62]. Chapters 4 and 5 of this dissertation present studies carried out in a collaborative laboratory context that required students to work in groups, but did not closely monitor or facilitate their interactions. Chapter 4 examines how students reason about physics in this environment [56], and Chapter 5 examines how students interact with each other in this environment [57].

In addition to interactive lectures and collaborative laboratories, many research-based pedagogies have been developed and implemented in university physics. SCALE-UP, studio physics, Modeling Instruction, ISLE, and problem-based learning (PBL) all take carefully designed approaches to transforming the physics lecture and/or laboratory experience [22, 32, 37, 39–43, 63, 64]. The aforementioned pedagogies are all centered fundamentally around group work. Students spend the vast majority of their class time working in small groups on conceptual or experimental tasks. Some pedagogies include large group synthesis and discussions, as well. All of these pedagogies tend to leverage several instructors in order to facilitate student interactions and learning in the complex environment that arises. Chapter 3 of this dissertation presents a study that took place in a carefully facilitated problem-based learning physics course, and investigates instructors' approaches to teaching computational problems in this environment.

2.2.2 Activities in collaborative learning

In addition to the format of collaborative learning environments varying, the tasks on which students work in these environments can vary greatly. Given that the laboratory context is often collaborative, it naturally follows that many times, students in collaborative learning environments work on experiments or other measurement and observation based exercises [19, 34, 41, 42, 62]. These sorts of activities do not only appear in laboratory courses, however. Pedagogies like SCALE-UP and Modeling Instruction incorporate experiments into their curriculum outside of a purely laboratory context [41, 42].

Collaborative learning also can incorporate conceptual questions regarding physics content. In the interactive lecture environments, the tasks that students collaborate on are often short, conceptual questions [20, 33, 35, 36]. Conceptual questions also play an important role in the SCALE-UP pedagogy, where they form the basis of short "ponderable" tasks, which students consider together [41]. Chapters 4 and 5 of this dissertation present studies in which students worked in groups on a series of brief, conceptual physics problems. Chapter 4 investigates their reasoning, and Chapter 5 investigates their interactions.

Some collaborative learning incorporates complex activities, which students spend significant time solving together [22, 32, 38, 42, 43, 65, 66]. In ISLE and Modeling Instruction, students work together to develop models and representations of physical phenomena over the course of a class session or sessions [22, 42, 43]. In problem-based learning, students work together to develop a solution to a contextualized problem where the goal and information given are not always straightforward [32, 37, 63, 64]. Chapter 3 of this dissertation presents a study that took place in a problem-based learning style course, where students worked on complex problems, including some which were computational, and investigates how instructors approach teaching the computational problems in this environment.

Aligned with the push to incorporate authentic physics practices such as programming [67, 68] into physics curricula, computational work is also becoming increasingly incorporated into collaborative learning environments [32, 54, 69–75]. We take computational work here to mean activities which involve the use of a computer to numerically model a physical situation, often via students writing and modifying code in a programming language. Such computational work has been incorporated into collaborative learning environments through the development of dedicated courses on scientific computing which incorporate collaboration [69], the incorporation of computation throughout the physics major experience [70], and through the incorporation of collaborative computational problems into individual physics courses [32, 71–74]. Chapter 3 of this dissertation presents a study in students collaborated on computational problems in a particular course that had been transformed to incorporate both collaboration and computation [32].

As the preceding review demonstrates, collaborative learning environments can take on many different forms and can require students to work on many different types of tasks. From interactive lectures to problem-based learning, and from traditional experiments to computational modeling problems, the landscape of collaborative learning is rich and diverse. This variation and the complexity inherent to environments in which students interact with not only the physics concepts, but also each other, makes it essential to study collaborative learning environments from multiple perspectives. Only through investigating the experiences of both students and instructors, and through implementing different scopes of analyses can the most complete understanding be achieved. The remaining sections of this Chapter will review the research that has been done on collaborative learning environments in physics, beginning with a narrow scope, focused on the unique position of instructors. We will then shift to research that has been conducted investigating the more diverse student perspective, focusing first on students' reasoning within these environments. Finally, taking the most expansive view, we will review the research that has been done on how students interact with each another in collaborative learning environments. This expanding focus mirrors the expanding of focus of the studies that will be presented in the Chapters 3 through 5 of this dissertation. Chapter 3 will present a study of individual instructors' approaches to teaching (specifically computational problems) in a collaborative learning environment, Chapter 4 will present a study of students' reasoning in a collaborative learning environment, and Chapter 5 will present a study of how students interact in a collaborative learning environment.

2.3 Instructors in collaborative learning environments

There has been a great deal of research done to understand instructors' actions, perceptions, and beliefs in collaborative learning environments. In any classroom, instructors inhabit a unique position, and in collaborative learning environments, that position can become even more demanding and varied. Studies on the instructor side of collaborative learning environments have a relatively narrow research focus, centering specifically on the unique instructor position. This narrowest focus is what the study presented in Chapter 3 of this dissertation investigates, examining how undergraduate learning assistants teach computational problems in a problem-based learning course. These learning assistants are individuals who were successful as students in the course who are invited to join the teaching team. While a more detailed review of relevant literature appears in Chapter 3, an overview of research on instructors in collaborative learning environments will be presented here. Our review of research on instructors will begin with an investigation of who they are and how they function in collaborative learning environments.

2.3.1 The roles of instructors in collaborative learning

In collaborative learning environments, instructors can take on many different roles. In some contexts, they function similarly to the way they would in a traditional lecture course. For example, in Peer Instruction and other interactive lectures, while the instructor takes on the new role of instigating and sometimes moderating small discussions, they still lecture to some degree from the front of the classroom and transmit information to the class as a whole [20, 34–36]. Instructors in collaborative learning environments can also act as synthesizers, bringing together diverse discussions and viewpoints shared in collaboration to a cohesive takeaway [36, 38, 41, 42, 76]. Instructors may also act as floating facilitators, giving groups of students individualized attention and instruction [32, 38, 41, 42, 76, 77]. Chapter 3 of this dissertation presents a study of instructor approaches to teaching in an environment in which the instructors function as floating facilitators, and do not engage in lecture or whole class synthesis at all. Finally, many collaborative learning environments are treated in a relatively "hands-off" fashion. Students work in groups, but are largely left to their own devices. Such an approach is commonly seen in traditional laboratory courses, for example. Chapters 4 and 5 of this dissertation present studies that took place in a largely unfacilitated collaborative laboratory context.

In addition to instructors functioning differently in different types of collaborative learning environments, instructors can come from different populations. Like traditional college learning environments, the majority of instructors in collaborative environments are faculty members, but they also often incorporate graduate teaching assistants and undergraduate learning assistants. Graduate teaching assistants in collaborative physics learning environments (and in physics courses in general) are typically graduate students of physics. They are therefore expected to have relatively strong disciplinary expertise, but the pedagogical training they undergo can vary greatly [78–81]. It should be noted that this is not vastly different from faculty members, who often also do not receive extensive pedagogical training [82, 83]. Perhaps the most unique and interesting population of instructors to consider, however, is undergraduate learning assistants [80, 84–87]. Since they are undergraduates, they naturally have not often developed the content expertise of faculty or graduate students. However, they have strengths that the faculty and graduates often do not. Learning assistants are not always physics majors, so they have expertise in other disciplines that physics graduate students and faculty members may not have. Additionally, learning assistants are often selected from students who have taken a course themselves in the past, and so they have a unique perspective, having experienced the course as a student. Chapter 3 of this dissertation presents a study of the approaches that learning assistants take to teaching in a collaborative learning environment. Having considered the roles that instructors may play and who instructors may be, our review will now turn to studies of how instructors enact their teaching in collaborative learning environments.

2.3.2 Instructor practices in collaborative learning environments

A natural place to begin the investigation of the instructor side of collaborative learning environments is to characterize what it is instructors do while teaching in these environments;

their practices. Some work of this nature has been done from the perspective of defining what instructors in particular pedagogies are meant to be doing [36, 37, 41, 42]. Other research on instructor practices is more descriptive in nature; analyzing what instructors do while teaching based on observations in the classroom. Such work has been done in various collaborative learning contexts. For example, researchers have investigated how instructors teach in laboratories [62], interactive lectures [52], collaborative problem-solving sessions [88], and collaborative classrooms [89]. While there is some work on graduate teaching assistant and undergraduate learning assistant teaching practices [90, 91], the majority of this work has investigated how faculty members teach in collaborative learning environments, leaving a gap in our understanding of how teaching and learning assistants teach.

Some research regarding instructors in collaborative learning environments has focused on their practices when teaching particular types of activities. As outlined in Section 2.2.2 of this chapter, there has been a move to incorporate computation into collaborative learning, and there has been research conducted on how instructors teach in these situations [74, 92, 93]. This has included work done at the pre-college level, investigating teachers incorporating technology-dependent activities in general [92, 93], and also work done at the college level, examining how instructors teach computational problems [74]. However, there has not been a great deal of work done in this area, and so there is a need to better understand how instructors teach computation in collaborative physics learning environments.

Given an understanding of what instructors do when teaching in these environments, many researchers have gone on to investigate instructors' perceptions and beliefs about these environments, that is, their opinions about, attitudes towards, and conceptions of collaborative learning environments. The last portion of this review of literature on instructors in collaborative learning environments will investigate this area of research.

2.3.3 Instructor perceptions and beliefs in collaborative learning environments

Bridging the gap between research on instructor practices and research on instructor beliefs, work has been done on relating instructors' actions to their beliefs about collaborative learning environments. Some of this work has aimed to use both beliefs and practices to come to a more cohesive view of an instructor's teaching [88, 89, 94], while other work has investigated how instructors' beliefs impact their practices [90, 91, 95, 96].

Some research has focused more completely on instructors' beliefs. This type of work is typically conducted via interviews, and aims to understand how instructors perceive collaborative learning environments and what beliefs they have about them, without trying to directly tie it to classroom practices. Research has been conducted investigating what beliefs instructors have about teaching and learning in collaborative problem-solving [85, 87, 97]. There have also been studies of what instructors believe good teaching is, and how they believe collaborative learning should be taught [55, 76, 98]. It is worth noting that again, despite there being some research on teaching and learning assistant beliefs [85, 87, 90, 91], much more research has been conducted on faculty beliefs.

Again zooming in on collaborative learning environments that incorporate computation, research has been conducted to investigate what beliefs instructors have about computation in these environments. Researchers have examined the beliefs of teachers incorporating interactive technology-based activities in the K-12 level, ranging from leveraging the use of the internet and computers in any way to incorporating computational modeling exercises [92, 93, 99]. There has been less work done investigating instructor beliefs about collaborative computational exercises at the college level [100–102].

Chapter 3 of this dissertation presents a study that fills two of the gaps in the literature on the instructor side of collaborative learning environments outlined here: a lack of research on learning assistant beliefs, and a lack of research about beliefs regarding collaborative computational exercises. The study takes a phenomenographic approach [54, 55] to analyze interviews conducted with learning assistants regarding their experiences and beliefs about teaching computational problems in a problem-based style introductory physics course. The study has a narrow scope, looking at the unique instructor perspective, and analyzing individual perspectives on teaching specific types of problems. This focus alone, however, provides only a small window in the complex system that collaborative learning environments present. In order to best understand them, it is essential to consider other participants' perspectives and to consider more expansive scopes. Chapter 4 of this dissertation presents a study that shifts to the student perspective of collaborative learning, and specifically investigates how they reason in these environments. The following section presents an overview of research on student reasoning in collaborative learning environments.

2.4 Student reasoning in collaborative learning environments

To best understand collaborative learning environments, they must be studied from multiple perspectives. Having considered the unique position of instructors, we will now turn our attention to the perspectives of students. Specifically, we will begin with a narrow focus on how students reason in collaborative learning environments. Chapter 4 of this dissertation presents a study investigating students' reasoning during a collaborative activity, specifically identifying a new epistemic game describing their problem-solving approach [56]. Our review of the literature on student reasoning in collaborative learning environments will begin with a background on frameworks that have been used to understand student reasoning.

2.4.1 Frameworks for understanding student reasoning

Several frameworks have been developed in order to understand student reasoning both in collaborative learning environments and outside of them. In physics education research, one perspective that was used often in early research was centered around the construct of student "misconceptions" [103–109]. In this perspective, students are considered to have specific, discrete, and relatively stable conceptual misunderstandings, and instruction is the process of replacing these "misconceptions" with the correct understanding of the concepts. This perspective can provide useful insights into student reasoning, but it is limited in its ability to describe the nuances of student ideas. Students' misunderstandings are not static and are not disconnected from their understandings of other concepts [11–13]. They may demonstrate a common "misconception" regarding a particular concept in one context, but be able to use that same concept correctly in a new context. This sort of contradiction indicates that students' ideas are not simple misconceptions that can be replaced by the instructor's expert-like conceptions. Instead, students ideas are highly contextual and dynamic, and it is productive to acknowledge this when building frameworks to understand student reasoning [12].

The resources framework accounts for this by taking a different approach. In the resources framework, students' understandings are imagined to be a network of different concepts and ideas about concepts, referred to as resources. When presented with a problem or put in a certain context, different resources are activated for a student, and these activation patterns are what lead to the understandings that a student expresses. With this framework, learning is then the process of providing students with new resources and helping them to form different activation patterns among their pre-existing resources [14, 15]. This framework not only attends more to the complexity of student ideas and their contextual nature, but also acknowledges the valuable ideas that they already have, rather than treating them as something to replace.

The "misconceptions" and resources frameworks provide two perspectives on the structure of student knowledge. Physics education research has also leveraged several perspectives on learning. The cognitive perspective treats learning primarily as the acquisition of new ideas. In the constructivist perspective, learning is the process by which knowledge is built through the learner's interactions with the world. In sociocultural perspectives, an emphasis is placed on the central role of social interactions in learning. The majority of the literature presented in this review of literature on student reasoning will take the cognitive or constructivist approach, however many studies presented on student interactions in Section 2.5 will provide examples of the sociocultural approach.

2.4.2 Quantitative approaches to understanding student reasoning in collaborative learning environments

A great deal of research has investigated student reasoning in collaborative learning environments through the use of quantitative measures. One common method of doing so is through the use of concept inventories. Concept inventories are typically multiple-choice tests probing students' understanding of some topic [16–18]. Concept inventories have been used widely in the assessment of student understanding in collaborative learning environments, often by measuring student performance before and after instruction or an intervention. For example, several studies have compared collaborative learning environments with traditional lecture environments, very often finding that collaborative learning leads to larger pre to post improvement on concept inventory scores [19–22, 110]. This type of measurement has also been used to assess the impact of specific types of collaborative interventions [111]. Concept inventories have also been used to investigate issues of equity, seeking to determine if collaborative learning environments can reduce the gap in scores that is typically observed between students from majority and minority populations [47–49]. Concept inventories are not the only measures used in quantitative studies of student reasoning, with others using problem sets, exams, or other assessments [23–25, 112, 113].

This type of work has natural limitations, however. By focusing on pre- and post-measurements of student understanding, these studies do not provide very much insight into the mechanisms by which students learn. They do not allow for observations of the ways that students reason together when working in groups. Furthermore, there are systematic issues with concept inventories in particular, as it is not always clear to what degree they really measure students' understanding of the content they purport to assess [114–116] and they may unintentionally support deficit views of underrepresented minorities [117]. In order to get a better understanding of how students reason as they collaborate, it can therefore be productive to take a more qualitative approach.

2.4.3 Qualitative approaches to understanding student reasoning in collaborative learning environments

Many studies have been conducted seeking to qualitatively examine how students reason and work through problems in collaborative learning environments. Some of these have taken explanatory or causal stances, attempting to explain the mechanisms by which students learn and reason while collaborating. For example, some work has proposed various processes by which learning may occur in collaborative environments [26, 118], or ways that effective collaborative reasoning must be structured [119]. Other qualitative work on student reasoning has been primarily descriptive in nature, offering ways to describe observations of student reasoning and problem-solving as they collaborate. One notable example of this is the construct of epistemic games. Epistemic games are emergent problem-solving strategies with which students are observed to engage [27–29]. They are productive in that they provide a way to understand the seemingly well-defined, but not explicitly stated or imposed, problem-solving methods that students may use. While many epistemic games have been identified in individual and collaborative learning environments, because students' engagement with collaborative learning environments, and the environments themselves, are so varied, the identification of new epistemic games is always insightful.

Chapter 4 of this dissertation takes a qualitative approach to investigating student reasoning in collaborative learning environments. Specifically, it identifies a new epistemic game, the shared answer-making epistemic game [56], a variation on an epistemic previously observed in individual students [29]. The shared answer-making epistemic game adds to the literature by offering a new lens through which to understand collaborative student reasoning, and also providing an example of how an individual epistemic game may be observed in a collaborative context. Student reasoning is only part of the complex system of collaborative learning environments, however. These environments must be studied from multiple perspectives and with different scopes of analysis in order to be best understood. The focus of Chapter 4 on student reasoning represents a focus on the student perspective, and a relatively narrow scope, attending specifically to students' interaction with the physics concepts. This represents an expansion from the even more narrow focus of Chapter 3, which will present a study on the unique instructor perspective, examined through individual interviews. Chapter 5 will continue the trend of expanding focus, by taking the largest scope and examining how students interact with each other in collaborative learning environments. An overview of the literature on the student interactions and other elements of the student experience beyond reasoning in collaborative learning environments will be provided in the following section.

2.5 Beyond student reasoning in collaborative learning environments

In order to come to the richest understanding of collaborative learning environments, they must be studied from multiple angles. Having considered the unique instructor perspective, then shifting to the broader student perspective, but limiting our scope to student reasoning, we will now shift to the most expansive focus; the elements of student behavior and experience in collaborative learning environments that go beyond the physics content. Chapter 5 of this dissertation presents a study taking this most expansive approach, describing the development of a framework for understanding student interactions in collaborative learning environments that attends to not only the physics they discuss, but also the way in which the structure their conversations, and the tenor of their interactions [57]. A more detailed review of the relevant literature will be presented in Chapter 5, but an overview of research on student experiences and behavior beyond physics content in collaborative learning environments will be presented here.

2.5.1 Student perceptions of collaborative learning environments

One area of student experiences beyond reasoning that has been examined in collaborative learning environments is how they perceive the collaboration itself and collaborative tasks. This has produced a variety results with a variety of areas of interest, including descriptions of what leads students to feel successful in when collaborating [120] and what students perceive the value of their peers to be when collaborating [121]. Students' perceptions in collaborative learning environments have also been investigated by examining the impact the learning environments have on students' attitudes and beliefs about science and learning [44–46, 64, 110, 122].

Much research on student perceptions of collaborative learning has made use of the constructs of framing and epistemological framing. Framing is the process by which a person or group interprets their surroundings, including the context and any task at hand [15, 30, 123], and epistemological framing describes this specifically with respect to students' framing of activities related to knowledge and learning [30]. Epistemological framing has been used productively to describe the different ways that students engage with each other and tasks in collaborative learning environments [30, 124, 125]. Such studies have resulted in both discrete [30, 124] and continuous [125] frameworks describing students' framing of collaborative tasks.

Students' perceptions and framing of their environment is only one of many facets of their experiences beyond reasoning in collaborative learning environments. Another highly salient aspect of their experiences is the interactions they have with each other, and work on this aspect will be reviewed next.

2.5.2 Student interactions in collaborative learning environments

Given that student interactions are a unique and crucial part of collaborative learning environments, it is no surprise that these interactions have been studied in many ways. The ways that students interact with each other can have a huge impact on how they learn and so it's essential to understand these interactions [126, 127, 133]. Some research has specifically been aimed at understanding what can account for the differences in how successful different groups of students are when factors such as their individual understandings and their demographics are unable to, and they have found that it is the types of interactions present in the groups that explain those differences [126, 127]. In order to better understand these different types of interactions, some work has sought to develop schemes for categorizing different types of interactions [128–131]. Some work has focused specifically on how groups of students navigate the conflicts that arise when they need to collaborate to complete an activity [31, 129, 130, 132]. There have also been studies aimed at understanding what kinds of interactions are most productive [133], and what kinds of interventions lead to the most productive student interactions [31]. Research such as this on how students interact in collaborative learning environments and the effects of those interactions provides an important piece in building our understanding of these learning environments.

Chapter 5 of this dissertation presents a framework developed in order to better understand how students engage in collaborative learning environments [57]. The Modes of Collaboration framework attends to three dimensions of their experiences: the tone of their social interactions, the structure of their discussions, and the physics content on which they focus. By attending to all three of these elements, the framework provides a rich picture of how students engage with collaborative learning environments that goes beyond their conceptual reasoning. This is still only one part of the complex system of collaborative learning environments, however. This most expansive view must be combined with other perspectives to develop the most robust understanding of these environments. This dissertation combines this expansive focus on student engagement with a more narrow focus on student reasoning in Chapter 4, and a narrower focus still on individual instructor perspectives in Chapter 3 in order to provide a multifaceted view of collaborative learning environments.

All three of these studies were carried out in physics courses at Michigan State University. An overview of this context will be provided in the following section.

2.6 Physics learning environments at Michigan State University

The studies presented in this dissertation were conducted at Michigan State University (MSU), a large public research university. MSU has a total undergraduate enrollment of over 35,000 students, with approximately 350 physics majors, and graduating approximately 35 physics majors each year. The physics major within MSU is unique in that a student may pursue it in two different colleges: the College of Natural Science or Lyman Briggs College. In the College of Natural Science, a physics major is part of the Department of Physics and Astronomy, which grants degrees in both physics and astrophysics. This conforms to a more traditional physics major experience, and all physics courses are taken through the Department of Physics and Astronomy. The Lyman Briggs College is a residential college for the sciences, in which most students live in the same dormitory, which also houses their introductory courses. A student pursuing a physics degree from this college will obtain the same degree as a student in the College of Natural Science, but may take their introductory level science and math classes through Lyman Briggs, which offers its own introductory series of courses. Students in the Lyman Briggs College also take several courses on the history, philosophy, and sociology of science. It is worth noting that students in either college may take either college's introductory physics courses. Chapter 3 of this dissertation presents a study that was conducted in the Department of Physics and Astronomy introductory mechanics course. Chapters 4 and 5 of this dissertation present studies that were conducted in the Lyman Briggs introductory electricity and magnetism course. A more detailed description of the different physics courses at MSU will now be provided.

2.6.1 Lyman Briggs

At the time of this research, the Lyman Briggs physics courses were taught primarily via interactive lectures and the required co-enrollment in a laboratory component, with the lecture and laboratory components typically having different instructors. It was a calculus-based physics sequence, which required one semester of calculus as a pre-requisite for the introductory mechanics course, and recommended a second semester of calculus for students taking the introductory electricity and magnetism course. In practice, however, both courses made relatively little use of calculus. The lecture component of the course met three times per week for one hour and had an enrollment of approximately 100 students. The students attended one three hour laboratory section per week in sections of approximately 20 students each. The students in the course were typically life science majors and sophomores. The course demographics were majority female with respect to gender, and majority white with respect to race.

In the lecture meetings, the class was taught in a highly interactive way. A great deal of time was spent soliciting student questions, encouraging student discussions, and engaging with clicker questions, and lecturing time was kept at a minimum. In the laboratory sessions, students worked in groups of approximately four on a variety of collaborative activities, including traditional experiments, tutorials, and conceptual and numeric problems. The laboratory sections were taught by pairs of undergraduate learning assistants, who received weekly training from the laboratory instructor. The learning assistants were students who had been successful in taking the course themselves previously. The course also employed a graduate teaching assistant who worked in both the lecture and laboratory components.

The studies presented in Chapters 4 and 5 of this dissertation were carried out in the laboratory component of the Lyman Briggs electricity and magnetism course while the author was serving as its graduate teaching assistant. Video data and written artifacts were collected from every section for one week as they worked on a series of conceptual questions regarding electric field and potential. This data provided insight into both how students reasoned about the concepts [56] and also how they interacted with each other [57] while working in this collaborative environment.

2.6.2 Department of Physics and Astronomy

2.6.2.1 Traditional courses

The majority of the introductory physics courses in the Department of Physics and Astronomy at the time of this research were taught in a traditional lecture style. There was no required co-enrollment in a laboratory section for the Department of Physics and Astronomy introductory physics courses. The Department of Physics and Astronomy offers both algebra and calculus based introductory sequences, with the former being taken primarily by life science majors, and the latter being taken primarily by physics and engineering majors.

The remainder of this overview of introductory physics at MSU will focus on the calculus based sequence. The demographics of the calculus based sequence were majority male with respect to gender, and majority white with respect to race.

The lectures meetings were taught in sections of approximately 300 students in large auditorium-style lecture halls, meeting three times a week for one hour. Instructors typically taught from the front of the room using projected slides. There was some variation among instructors with respect to fostering an interactive lecture through the use of clicker questions or peer discussions, but many instructors relied primarily on traditional lecturing. These sections typically did not employ graduate teaching assistants or undergraduate learning assistants, outside of grading assistance.

In addition to the traditional lecture style, the Department of Physics and Astronomy now also offers a problem-based learning style of the calculus based introductory sequence. This is the context in which the study presented in Chapter 3 was carried out, and it will be described in greater detail in the following section.

2.6.2.2 P Cubed

Shortly before the research presented in this dissertation was conducted, a problem-based learning version of the Department of Physics and Astronomy introductory mechanics course was developed, known colloquially as Projects and Practices in Physics, or "P Cubed" [32]. P Cubed has the same course number and satisfies the same requirements as the traditional lecture sections; it is simply another section of the same course that students may choose to enroll in. P Cubed is open to any student and does not require special permission to enroll, and it is explained explicitly as being taught in a problem-based learning style on the online course registration platform. P Cubed was piloted with a 40 student section, but now is taught to a 100 student section. The students in P Cubed are primarily engineering majors and sophomores. The demographics of P Cubed are majority male with respect to gender, and majority white with respect to race, however the gender demographics are closer to parity than those of the traditional sections.

In P Cubed, there is no lecture whatsoever, and instead students spend every class session working on a complex problem in groups of four. The course meets for two hours twice a week, and there are four three hour long evening exams over the course of the semester. The problems that students work on in P Cubed are designed to be complicated and require significant collaboration, planning, and investigation. Students often must seek out additional information online, or must ask an instructor for additional information. P Cubed also incorporates computational problems. While most of the problems are analytic, that is, solved by hand, approximately five problems throughout the semester are computational. In the computational problems, students are given a prewritten portion of code that will run and render a visualization of a physical scenario, but will not correctly model the physics of the situation. Their task on computational problems is to modify and add to the code to make it properly reflect the physics. P Cubed is taught by a team comprised typically of one or two faculty members, a graduate teaching assistant, and 12 undergraduate learning assistants. The undergraduate learning assistants are selected from students who were successful as students in P Cubed. In the classroom, all members of the teaching team function identically regardless of their "rank", with each being responsible for facilitating two groups of students and ensuring that they develop an understanding of the concepts.

Chapter 3 of this dissertation presents a study regarding the P Cubed section of the Department of Physics and Astronomy introductory mechanics course after it had scaled up to a 100 student enrollment. Specifically, interviews were conducted with learning assistants regarding their experiences teaching the computational problems. These interviews resulted in the development of a set of categories that describe different approaches learning assistants may take to teaching computational problems in problem-based learning environments.

2.7 Closing

This concludes our overview of the literature on collaborative learning environments and the collaborative learning environments at Michigan State University. Like the three studies presented in Chapters 3, 4, and 5, our review of the literature began with a narrow focus on the instructor perspective in collaborative learning environments, then shifted to the broader student perspective, first with a targeted focus on student reasoning, then with a more expansive focus on student engagement with collaborative learning environments beyond conceptual reasoning and understanding. While a more detailed review of the relevant literature and methodologies will be provided in the chapters devoted to each study, this background gives a broad perspective on collaborative learning environments and those at Michigan State University.

We will proceed now to the first of the three novel studies presented in this dissertation, and the one with the finest focus: learning assistant approaches to teaching computational problems in a problem-based learning course.

Chapter 3

Learning assistant approaches to teaching computational problems in a problem-based learning course

3.1 Introduction

In order to meet the repeatedly identified need for well-prepared STEM majors in both modern academia and industry [1–5], undergraduate physics education has adapted in many ways [6–10]. One strategy has been the increased incorporation of collaborative learning activities and the development of collaborative learning environments. In these contexts, students work primarily with each other in groups, with instructors facilitating their work rather than lecturing [22, 32, 37–43]. Problem-based learning, for example, has students work in groups to solve complex problems framed in realistic contexts, often without explicitly stated questions [32, 37, 63, 64]. Problem-based learning environments can require careful facilitation to ensure that students are having productive learning experiences. Instructors may need to moderate group dynamics and guide students' learning in a way that isn't demanded of them in a traditional lecture course [37, 76, 77, 134]. This context offers a rich environment in which to study instructors' enacted teaching methods, that is, their practices, and their opinions and perceptions of teaching and learning, that is, their beliefs.

To give students this level of attention, collaborative learning environments often employ teaching assistants in addition to faculty members [77, 79, 80, 84, 135]. These teaching assistants may be graduate students, or undergraduate students, with the latter often referred to as learning assistants. Learning assistants are a unique population of instructors, as they may be best suited to understand their students' perspectives, and also may not have a great deal more experience with the content than their students [80, 84]. The teaching practices and beliefs of learning assistants have not been greatly studied however [85–87], and so there is a need for further research on this group.

In tandem with transforming the structure and instruction of learning environments in these ways, there has been a push to incorporate authentic practices into physics education in order to better prepare students for academia and industry [67, 68]. One particular practice that has had an increasing emphasis is computation [32, 68–74]. The practice of modern science relies on the use of computers to model and simulate phenomena that are impossible or impractical to study analytically, but historically, students have received little explicit instruction in these skills [68]. Computational exercises, that is, exercises which require students to model or simulate physical scenarios numerically, are beginning to be more incorporated into undergraduate physics courses. Studying the ways in which these are being implemented and taught is important for making them as productive as possible for students.

We conducted a study taking place at the intersection of these three unique developments in physics education: problem-based learning, undergraduate learning assistants, and computational problems. We interviewed learning assistants who had taught in a section of an introductory mechanics course that is taught in a problem-based learning style and that incorporates several computational problems. Our aim was to examine how they approached teaching computational problems in this environment, because understanding how these uniquely positioned and not often studied members of the teaching team work in such a complex environment provides valuable insight into how we can best design and implement computational work for students, and gaining such insight will be increasingly important as computation becomes more prevalent in physics curricula. In particular, better understanding how learning assistants approach teaching computational problems could allow for the development of training and supports that encourage them to teach in ways that are most in line with the course goals surrounding computation. To examine the learning assistants' approaches to teaching computational problems, we conducted a phenomenographic analysis [54, 55, 136, 137] of interviews with 12 physics learning assistants, resulting in the development of four approaches they may take to teaching computational problems in a problem-based learning course. This chapter presents these approaches, the process of their development, and their implications, and Appendix A provides an expanded description of the analysis process.

3.2 Background

The study presented here took place in a very unique context. The participants were undergraduate learning assistants, a relatively little studied population [84–87], the course was taught in a problem-based learning style, a context rich with complex interactions among students and instructors [37, 63, 64, 76], and the course made use of computational problems, a unique type of activity at the center of the push to incorporating authentic practices into physics education [32, 68–74]. A review of the literature on these three subjects will be provided here.

3.2.1 Problem-based learning

Problem-based learning was developed in the field of medical education in order to give medical students better opportunities to apply their knowledge in realistic scenarios [138, 139]. Since then, it has been adopted in many contexts, across different education levels and disciplines [37, 63, 64, 134, 140]. Problem-based learning is founded upon a shift from the instructor-centered approach of traditional lecture environments, to a student-centered approach, wherein students must navigate complex problems together [37, 63, 64, 77, 134]. There are a variety of definitions and implementations of problem-based learning, but these learning environments are often characterized by students working in collaborative groups, instructors functioning as guides rather than lecturers, and problems that require students to leverage decision-making, planning, and problem-solving skills. The goal of these learning environments is that students develop conceptual understandings and discipline-relevant skills through the process of their largely self-directed work through the problems [37, 63, 64, 134, 138, 139]. The dynamic structure and complex tasks in problem-based learning environments make them a rich environment for educational research, and such research has been done on the perspectives of both instructors and students.

The student perspective of problem-based learning has been studied in several ways. Many quantitative studies have measured the conceptual learning of students in these environments and found that they are more effective than traditional pedagogies [37, 110, 113, 122, 141]. Dochy et al. conducted a meta-analysis of such studies and found that they overwhelmingly indicated that problem-based learning has positive impacts on students' learning [113]. Barron et al. found that middle school students' learning improved by several metrics when they engaged in problem-based learning activities [37]. In post-secondary physics education specifically, multiple studies have echoed these results. Van Kampen et al. found that students' exam performance improved after the development of a problem-based learning module [141]. Selcuk et al. investigated the impact of problem-based learning on pre-service teachers in a physics course and found that it improved their achievement on physics activities [122]. Using the Force Concept Inventory, Sahin et al. found that students who had engaged in problem-based learning had greater learning gains than those in traditionally taught courses [110].

Several studies have measured the impact of problem-based learning on student engagement and perceptions. In the previously mentioned study by Van Kampen et al., results also indicated that the problem-based learning module they implemented had a positive effect on how interesting and relevant students found the physics content [141]. Ahfeldt et al. conducted a quantitative study to assess the impact of problem-based learning on student engagement, and found that it resulted in greater engagement than traditional courses [142]. Selcuk et al. similarly found that problem-based learning increased students' interest [122]. Results have not been universally positive, however, with Sahin el al. finding that problem-based learning did not appear to have any benefits over traditional courses when comparing student attitudes and beliefs as measured by the Colorado Learning Attitudes about Science Survey [110].

There has also been research examining other aspects of students' experiences in problem-based learning environments. Raine et al. found that students perceive problem-based learning to effectively model how work is done outside of classrooms. They also found that students are cognizant of and appreciate the approach to learning that problem-based learning encourages [63]. Selcuk et al. similarly found that problem-based learning was effective at encouraging students to take up a deep approach to learning [122]. Through interviews with students, Cockrell et al. identified "ownership of knowledge" as a salient characteristic of problem-based learning to students, with it being discussed in three contexts: group dynamics, tutor feedback, and metacognitive awareness [64]. Chiriac developed a framework to identify and describe the group processes that students engage in when working in problem-based learning environments [131].

Less work has been done on the instructor perspective of problem-based learning environments, despite the fact that these environments require just as radical of a shift in approach of instructors as they do of students [37, 76, 77, 134]. While instructors in lecture-based environments may attend primarily to the transmission of content, problem-based learning environments require instructors to interact with their students, foster productive interactions among their students, and allow students to approach the problems in their own ways, while still guiding them towards conceptual understanding. These considerations are complex and result in a myriad of approaches and beliefs that instructors may bring to problem-based learning. Barron et al. identified several design principles that instructors should consider when developing problem-based learning activities [37], while Maudsley discussed the ways that instructors must function in problem-based learning environments [77]. Abrandt et al. interviewed instructors who implemented problem-based learning and found notable variations in their perceptions. They found that teachers considered problem-based learning from either the teacher perspective or from the learner perspective, and that they viewed their role to be either supportive or directive [76].

It is important to understand the perspective of instructors and how they approach their teaching in problem-based learning environments, as their practices will greatly affect students' learning and experiences. In particular, the way that more junior instructors in problem-based learning environments, such as undergraduate learning assistants, enact and perceive their teaching merits further study. Learning assistants can often comprise the majority of the teaching team in a problem-based course, and so understanding how they approach their teaching is essential to understanding these classrooms.

3.2.2 Learning assistants

The complex and collaborative nature of problem-based learning often requires greater facilitation than traditional lecture courses. In order to ensure that students are developing conceptual understandings of the physics content as they work through the complex problems, instructors must carefully guide their progress and be aware of their conversations and work [37, 76, 77, 134]. To do this effectively, problem-based learning courses may employ teaching and learning assistants. Learning assistants provide a unique perspective, often being closer in experience with the content to their students than faculty members and graduate teaching assistants.

A particularly robust learning assistant program is in place at the University of Colorado Boulder, where the the first official learning assistant program was developed, and where the term "learning assistant" was coined. In the model developed at University of Colorado Boulder, the learning assistant program is framed as not only a means to provide greater facilitation in their courses, but also as an opportunity to build the next generation of science teachers and make students more aware of the possibilities for teaching careers in STEM [84, 143]. Much of the currently available research on learning assistants in physics has taken place in this context. There have been studies by Pollock et al. and Otero et al. conducted on the effects of employing learning assistants on student learning and course transformation sustainability, indicating that learning assistants have a valuable and positive impact on students and courses [84, 135]. There has also been work done by Spike et al. examining how to best prepare learning assistants for their teaching assignments, resulting in the development of particular pedagogical models for learning assistant training [80]. Researchers have also investigated the long-term effects that participating in the learning assistant program has on individuals who go on to become teachers. In a study based on teaching observations, Gray et al. found that in-service teachers who had been learning assistants scored higher on measures of interactive teaching methods than peers who had not been learning assistants [86]. In a similar comparative study based on interviews with in-service teachers, Gray et al. found that former learning assistants were more comfortable implementing group work in their classrooms and were more likely to state that building a learning community was a goal in their implementation of group work [85]. Gray et al. also examined how current learning assistants described their use of questions when facilitating recitation sessions of introductory physics courses, finding that their comments suggested several different goals in asking questions, and several different perceptions of their role as a learning assistant, including facilitating physics content, facilitating students' sense-making, shaping the learning environment, and professional growth [87]. Learning assistant programs have been implemented at other institutions as well, such as Florida International University [144] and Texas State University [145], but research is relatively limited currently.

These studies provide valuable insight into learning assistants, however they have limitations. The learning assistants studied in the aforementioned studies worked in a variety of types of learning environments. For example, some worked in recitation sections where students worked on physics tutorials, which are relatively linear activities, with well-defined questions for students to answer sequentially [146]. This sort of activity is very different than the complex problems in problem-based learning, which can require students to determine their own goals and questions and may have multiple possible solutions [32]. This difference could lead to differences in how learning assistants approach and perceive teaching, and it is the teaching approaches of learning assistants in a problem-based learning course that we examine in this study. In particular, we focus on how they perceive teaching problems that require students to engage in computational modeling, and we will review the research on computational activities in physics education next.

3.2.3 Computation in physics education

For the past several decades, STEM education has increasingly incorporated computer-based activities and computational activities into the classroom [74, 101, 147–149]. While computer-based activities can be as simple as leveraging the internet for instruction and homework, "computational activities" here will refer to tasks which require students to engage in the numerical modeling, analysis, or simulation of phenomena. Physics education has pushed to incorporate these sorts of computational activities in the curriculum, as they provide students with valuable practice engaging in an authentic aspect of modern science, and also can aid students' understanding of physics concepts [68]. Early examples of computational activities in physics education include the Berkeley BOXER project and the Maryland University Project in Physics and Educational Technology (MUPPET) [74, 148, 149]. These environments were very open, engaging students with the act of programming and giving them a great degree of control. In contrast, in another early example, the Physics Educational Technology simulations (PhETs) are relatively closed, giving students the ability to vary some parameters of a physical situation, but not making the underlying programming visible to them [147].

Some implementations of computational problems take elements of both styles, making some code visible and modifiable, but not expecting students to write programs from the ground up. In the field of biology, Wilensky et al. had students model biological phenomena in a computational platform that required them to write logical "rules" controlling the simulation, but did not engage them with more typical programming syntax [75]. In several different contexts, Caballero et al. developed computational physics problems in VPython, a variation of the Python language containing elements making it well suited to visual modeling. In these problems, students are given code that will run, but that does not yet correctly model the physical situation, known as "minimally working programs". Students' task is to then modify and add to the code so that it correctly reflects the physics of the situation [71, 72]. This type of problem design is similar to the approach that Chabay et al. had taken previously to incorporating computational problems [73]. In addition to these various designs, computational problems can be incorporated into curricula in different ways. At Oregon State, computational problems like these have been intentionally woven into courses across the curriculum [70], while Kaplan describes the development of a stand-alone course on scientific computation at Macalester College [69]. Often, however, computational problems are incorporated into courses on an individual basis at the discretion of the instructor. Given this wide variation in how computational problems are implemented and their increasing incorporation into STEM education, research has been conducted in order to better understand how students and instructors experience and engage with these problems.

Research on the student experience of computational problems often focuses on assessing students' abilities to engage with the problems, and what identifying difficulties they encounter [71–73, 75, 150]. Chabay et al. found that when working on computational problems, students had more opportunities to use creativity in their problem-solving and were better able to see connections across physical phenomena, however they sometimes struggled due to their lack of programming experience [73]. When students engaged in computational modeling using the logical rule-based format in the context of Wilensky et al., they were able to complete more complex problems, and engaged in more spontaneous question-asking and exploration [75]. Caballero et al. found that the majority of students who had engaged in their style of computational problem were able to successfully solve new computational problems. They also observed that the students who were unsuccessful in the new problems had errors that suggested that a misunderstanding of the physics was limiting them, rather than indicating that the programming was a barrier to their success [71, 72].

Some research has taken a broader approach when investigating the experiences of students working on computational problems. Lewis and Shah observed students working on pair programming exercises using an equity perspective, noting what inequities arose and suggesting methods to mitigate them [151, 152]. Other studies have taken a phenomenographic approach to identify the different ways that students experience computational exercises. Booth et al. found four different approaches that college students in a programming class would take to their programming: structural, operational, constructual, and expedient [54]. In a similar phenomenographic study of introductory programming students, Bruce et al. identified five experiences that students may have with respect to programming: following, coding, understanding and integrating, problem-solving, and participating, with each representing a student taking on a more expansive view of programming [153]. Studies such as these, and those on student achievement and difficulties regarding computational problems provide just one perspective, however, and it is important to also consider the teaching beliefs and practices of instructors who implement such problems.

Some research regarding instructors who incorporate computation into their classrooms has simply sought to identify the obstacles they perceive and to develop methods to help instructors overcome those barriers to implementation, such as that by Niess et al. [93]. With a similar motivation, Koehler et al. investigated the experiences of faculty and graduate students who took part in a workshop on incorporating technology into their courses, and found that having the experience embedded in their scientific disciplines had a significant impact on their perceptions [102]. Yerrick et al. examined the effect that perceived obstacles have on the different ways that teachers implement computational activities [99]. Hennessy also investigated variations in teachers' implementation of computational activities, finding several salient aspects of the teachers' experiences, such as leveraging the dynamic nature of simulations, focusing students' attention on key concepts, and often employing a teacher-directed facilitation style [92]. Phenomenography has also been applied to the instructor perspective of computational problems, as it was to the student perspective by Booth and Bruce. Magana et al. interviewed faculty teaching undergraduate and graduate STEM courses that implemented computational simulation exercises. They found eight different intended outcomes that instructors may have in incorporating computation into their courses: to become aware of the role of computation in science, to make measurements, to find causal relationships in models, to test models, to validate results, to use computational techniques, to predict behavior, and to discriminate among possible models. They further argued that these eight intended outcomes represent increasingly higher order levels of thinking [100]. This sort of research on the perceptions of instructors is essential to understanding the implementation of computational problems, because instructors' beliefs and goals greatly impact how computational activities are carried out in practice [99].

The research on computational activities in physics (and STEM) education reviewed here gives a broad picture of ways computation is being implemented, how students perform on computational activities and what they struggle with, what instructors struggle with when teaching them, and some of the perceptions instructors have regarding them. While there has been some work done to qualitatively understand students' experiences of computational problems [54, 153], there has been less done investigating the experiences of instructors [100]. Computational problems require instructors to attend to not only science content, but also computational practices in their teaching. Depending on the structure of the course, instructors might additionally need to carefully facilitate group interactions and problem-solving processes, as in problem-based learning. The research presented here takes place in a problem-based learning course that incorporated computational problems and that employed undergraduate learning assistants [32]. Teaching computational problems in this environment can be complex and challenging, and it is important to understand how instructors approach that challenge. In particular, better understanding the approaches and perceptions of learning assistants can allow us to better support their teaching and their development as teachers. In order to investigate the learning assistants' approaches, we employed phenomenography as our method, which will be described next.

3.3 Methodology

The research question at the heart of this study was: what are the different approaches that learning assistants may take to teaching computational problems in a problem-based learning physics course? In investigating this question, our goal was not to describe what methods they use in practice based on observations of their teaching, but rather to understand the approaches they identify with based on their opinions and self-described experiences. Phenomenography is a method uniquely suited to this type of study, wherein one seeks to identify different categories describing the ways that a group of individuals may experience a phenomenon.

3.3.1 Phenomenography

Phenomenography developed as a research methodology in the 1970s through the work of Marton et al. in the context of education research as a means to understand student experiences [154, 155]. Marton defined it as the study of the variations in the ways individuals perceive and understand phenomena, taking a relational stance, that is, arguing that the phenomena are not separate and exterior to the individual, but experienced through a relationship [156]. Phenomenography rests on the assumption that although individuals experience a given phenomenon in unique ways, by probing a group of individuals' experiences, one can uncover the essential variations in how they experience the phenomenon. These variations represent the underlying differences in experience that emerge when considering the group as a collective, and not differences observed by directly comparing individuals [157]. As a result, variations may appear not only across individuals, but also within individuals. Indeed, a phenomenographic study does not seek to account for the entirety of a given individual's experience of the phenomenon, nor does it seek to identify variations that allow for each individual to unambiguously exhibit only one variation of experience. Instead, the objective is to use the individuals' experiences to identify meaningful variations that give insight into how the collective may experience the phenomenon [137, 157, 158].

The goal of a phenomenographic study is to find a set of categories that capture the variations in individuals' experiences of the phenomenon [54, 137, 156, 158, 159]. These "categories of description" should satisfy several criteria. Each category should describe a distinct way of experiencing the phenomenon of interest, the categories should have a logical relationship to one another, and the set of categories should be as concise as possible while still capturing the essential variations. The logical structure relating the categories is know as an “outcome space”, and the outcome space is often hierarchical. In a hierarchical outcome space, categories represent increasingly sophisticated and detailed ways of experiencing the phenomenon. The hierarchical nature of many outcome spaces can provide a great deal of insight into individuals’ experiences of the phenomenon. For example, since a given individual may exhibit several variations, if these variations represent different levels of sophistication of experience, we can gain insight into how individuals progress through the hierarchy to develop more sophisticated perceptions [160, 161].

A great deal of phenomenographic work has focused on approaches to teaching and learning. A common result from these studies are such hierarchical outcome spaces, describing the identification of increasingly sophisticated levels of teaching and learning [54, 100, 153, 162–166]. These results have great practical value in understanding learning environments, because they provide insight into how students adopt more sophisticated approaches to learning, and how teachers develop more sophisticated approaches to teaching. In this study, we investigated the teaching approaches of learning assistants, and specifically, their approaches when teaching computational problems in a problem-based learning course. By employing phenomenography, we were able to identify the underlying variations in how they approach teaching in this context, gaining insight into their beliefs as teachers and how we might support their development as teachers. In the next section, we describe the design of our phenomenographic study.

3.4 Study design

3.4.1 Study context

This study investigated the experiences of undergraduate learning assistants who had taught in an introductory calculus-based mechanics course. The course was a transformed section of the traditional lecture style course that is taught in problem-based learning style, known as "Projects and Practices in Physics" or "P Cubed" [32]. In its implementation of problem-based learning, P Cubed makes no use of lecture, and instead, students spend all time in the classroom working in groups of four on complex problems. These problems are written in such a way that they require that students work together and think intentionally about their problem-solving process. Over the course of the semester, approximately 5 of the problems are computational. In the computational problems, students are given a physical situation that highlights the physics concepts being taught that week, and they are given a portion of VPython code. The code they are given functions in that it will run without error, but it does not yet correctly model the physics relevant to the situation. The students' task for the class period is to modify the code such that it does correctly model the situation. The correctly modified code will render a visualization of the situation and/or graphs of physical quantities present in the situation. An example of a computational problem assigned in the course appears in Appendix B.

P Cubed meets for two hours twice a week, and has an enrollment of 100 students, most of whom are sophomore engineering majors. The course is open to all students, with enrollment occurring on a first come, first serve basis. Additionally, the course description on the university registration website makes it clear that it is taught in a problem-based learning style. P Cubed is taught by a teaching team composed of one or two physics faculty members (changing each semester), a graduate teaching assistant, and approximately 12 undergraduate learning assistants. The learning assistants are individuals who were successful as students in the course who are then invited to become instructors in the course. Corresponding to the student demographics, the learning assistants are primarily engineering majors. Learning assistants are invited to continue teaching the course as long as they are interested and available, and most choose to teach for several semesters.

In the classroom, all members of the teaching team function identically. Each instructor is responsible for two groups of students, guiding their progress through the concepts and problem of each day. Outside of the classroom, the teaching team has two pre-class meetings every week (the day before each class session), and a post-class meeting at the end of each week. In the pre-class meetings, the learning assistants work through the next day's problem in small groups, facilitated by the faculty members or graduate teaching assistant. In these meetings, the learning assistants have the opportunity to make sure they understand the concepts and solution themselves, and are also encouraged to think about how they will help their students navigate the problem and concepts. At the post-class meeting, all members of the teaching team summarize how their teaching went that week, and they can solicit help for any issues they are facing. Every member of the teaching team is responsible for writing individualized feedback for each of their students regarding their work that week. In addition to the aforementioned on-going responsibilities, the learning assistants also attend a day long training workshop at the beginning of each semester, which goes over in class teaching strategies, writing feedback, and course logistics.

Major	Number
Mechanical engineering	3
Biosystems engineering	1
Physics	3
Chemical engineering	1
Biochemistry	1
Computer science	1
Chemistry and Criminal justice	1
Biochemistry and Molecular biology	1

Table 3.1: Majors of the learning assistants interviewed

3.4.2 Data collection

The participants in this study were 12 learning assistants from P Cubed, who had taught for at least one semester over the 7 semesters of the course's existence at the time of this study. They varied in major, class rank, gender, and semesters of experience teaching in P Cubed, shown in Tables 3.1, 3.2, 3.3, and 3.4. They also had a wide variance in personal experiences with teaching and computation outside of P Cubed. These differences led us to believe that this would be a productive population for conducting a phenomenographic study, which depends on identifying variations as described previously [54, 137, 158, 159]. In order to conduct a phenomenographic analysis of the learning assistants' approaches to teaching computational problems, we investigated their experiences via interviews. It is worth noting that the interviewer had a personal familiarity with the participants, as she had been a graduate teaching assistant in P Cubed and had worked with each of the participants. The interviewer strove to minimize any bias this might result in during the interviews and ensuing analysis.

The development of the protocol for these interviews and the interview process will be described in the following sections.

Class rank	Number
Freshman	0
Sophomore	2
Junior	4
Senior	6

Table 3.2: Class ranks of the learning assistants interviewed

Gender	Number
Female	7
Male	5

Table 3.3: Genders of the learning assistants interviewed

Semesters of experience	Number
1	2
2	3
3	2
4	2
5	2
6	1

Table 3.4: Semesters of experience teaching in P Cubed of the learning assistants interviewed

3.4.2.1 Interview protocol development

In line with the goals of a phenomenographic study and with our phenomenon of interest, approaches to teaching computational problems, we developed a semi-structured interview protocol aimed at probing the learning assistants' experiences teaching computational problems [159, 167–169]. The semi-structured nature of the protocol allowed for the interviewer to follow emergent threads that were salient to the participant, while also being sure to get as complete a picture of the individual's experience as possible. The questions on the protocol were developed based on several considerations. Of course, the majority of the questions directly probed their experiences and opinions on teaching computational problems in P Cubed. In addition to these questions, however, questions on the participants' backgrounds, opinions on the course structures (feedback, collaboration, et cetera), and general opinions on teaching and learning were included. These were included in order to better contextualize their responses regarding the computational problems, and to also provide them with additional spaces to discuss computation and computational problems if they chose. The protocol underwent two rounds of revisions based on two pilot interviews. These revisions primarily involved restructuring the protocol in order to better follow conversational flow, and adding the questions regarding general opinions on teaching and learning, which had not been present in the initial version of the protocol. The interview protocol is presented in Appendix C.

3.4.2.2 Conducting interviews

The interviews were conducted over the course of approximately one year, based on the availability of the interviewer and participants. Participants were solicited by contacting current and former P Cubed learning assistants, inviting them to participate and explaining the goals of the study, the nature of the interviews, and the compensation offered (a $10 gift card). The interviews were conducted one-on-one between the interviewer and each learning assistant, and lasted approximately one hour and fifteen minutes. The interviews were open to following topics that the participants brought up spontaneously, and the questions on the interview protocol were not all explicitly asked in each interview or asked in the same order. The goal of the interviews was to develop as rich an understanding of the learning assistants' experiences as possible, so the primary goal throughout each interview was to provide the participants with as many opportunities to share their experiences in the ways that were most salient to them [159, 167–169]. The interviews were audio and video recorded, and the audio recordings were sent to an external company for transcription. Once the transcripts were received and reviewed for accuracy, analysis began.

3.5 Analysis

The following section describes the analysis procedures carried out in developing the categories of description identified in this study. Phenomenographic analyses require several iterations and modifications [54, 137, 158, 159], and so an abridged accounting of the process, highlighting key steps will be presented here. For a complete description of the analysis, see Appendix A.

3.5.1 Data reduction

Analysis began with reviewing all the transcripts several times in order to become familiar with the data set as a whole. After gaining familiarity with the full data set, the data was reduced based on relevance to the phenomenon of interest. Because the interviews were open to following tangents, and because several background questions were asked (see Appendix C), there were portions of the transcripts that were not relevant to the participants' experiences with teaching computational problems. For example, participants may have discussed their motivations for becoming learning assistants, or described their teaching explicitly with respect to analytic problems. In an example of the latter, one learning assistant spoke about teaching the analytic problems, which occur on Tuesdays,

> On Tuesday, the first question I'll ask them is, "What do you ultimately need to get? Where is your end goal?" They say, "Oh, this is our end goal." "Okay, what are the steps you need to take to get that?" That's on a Tuesday.

Portions of transcript such as these were neglected for the thematic analysis described next since they were not directly relevant to our phenomenon of interest, but they were retained in order to provide fuller context for participants' comments if necessary.

3.5.2 Identification of preliminary themes

Once identified, the reduced data set was analyzed for emergent themes in participants' discussion of teaching computational problems. These themes represented trends and common threads in what the participants spoke about over the course of the interview. Some of these themes corresponded to questions that were directly asked by the interviewer, while others did not. In either case, the themes were identified based solely on the comments of the participants in the transcripts, and the researchers strove to analyze the transcript without bias towards any particular themes emerging. This process resulted in a preliminary set of seventeen emergent themes shown in Table 3.5. These themes do not account for all of the reduced data set. Some relevant portions of transcript were too unique or specific to be

Preliminary Themes
Differences between analytic and computational teaching
Written feedback
Varying levels of student programming experience
Different student approaches to computation
Differences in student behavior solving computation versus analytic problems
What students should do when solving computation problems
Acceptable places to end computation days
Minimally working programs
Solution manuals
Why code in groups
Student challenges
Teaching challenges
Teaching physics versus teaching coding on computation days
In-class teaching strategies
Important things for students to take away
Purpose of computation
Student frustration

Table 3.5: List of preliminary emergent themes identified in the data

sorted into a theme. Examples include a learning assistant speaking on very specific role that he plays as computation expert on computation days, or extra preparation that a learning assistant engages in before she teaches computational problems. While these comments were interesting, they were not further analyzed. Since the goal of this study, and of any phenomenographic study, is to find the most concise way to capture the different ways that individuals may experience a phenomenon [54, 137, 158, 159], it is expected that not every relevant comment from the participants will be identified as belonging to a theme.

It is also worth noting that these themes are not necessarily mutually exclusive, and that there are portions of transcript that were coded as belonging to multiple themes. This is because in a given comment, a participant often discusses several dimensions of their experience at once. Thus one would not expect, and it is not a requirement that the themes be wholly orthogonal.

Teaching Outcome Variations	
Variation	Description
Programming skill	a familiarity with the syntax and structures of code
Physics-code connection	an understanding of the relationship between the computational problems and the physics concepts
A new approach to learning	new perceptions and beliefs about learning
Capabilities of computation	an appreciation of the usefulness of computation

Table 3.6: Variations within the *teaching outcome* theme, describing learning assistants' goals for their students

3.5.3 Analysis of preliminary themes

Once preliminary themes had been identified, individual themes were selected and examined in more detail to identify the variations in how the learning assistants discussed them. This analysis began with the investigation of the themes that were most richly populated, and which had the strongest apparent tie to our phenomenon of interest. These themes were *in-class teaching strategies*, *differences between analytic and computational teaching*, and *teaching physics versus teaching coding on computation days* since all three had explicit references to how learning assistants teach in the classroom, along with *important things for students to take away* since it appeared to be related to learning assistants' motivations for their teaching. Through the process of identifying emergent variations within these preliminary themes, they were ultimately reorganized into three new themes: *teaching outcome*, *teaching strategy*, and *characteristic to moderate*. These three themes and their respective variations are shown in Tables 3.6, 3.7, and 3.8.

Teaching outcome refers to what a learning assistant hopes their students gain from working on the computational problems as a result of their teaching. *Teaching strategy*

Teaching Strategy Variations	
Variation	Description
Focus on navigating programming errors	identify and help students overcome programming errors
Encourage reflection on coding	promote deeper thought on the function of computation
Leverage collaboration	stimulate group discussion of ideas
Leverage affordances of computational problems	utilize elements unique to computational problems in teaching

Table 3.7: Variations within the *teaching strategy* theme, describing the techniques learning assistants use while teaching

Characteristic to Moderate Variations	
Variation	Description
Student attitudes	prevent students from becoming too unhappy
Student attention to programming details	avoid students focusing on coding idiosyncracies
Student work pace	ensure students complete the activity
Impact of course design	mitigate the effect of the limitations of course structures

Table 3.8: Variations within the *characteristic to moderate* theme, describing what aspects of a group's experience a learning assistant feels they must monitor and influence

refers to the techniques that a learning assistant may employ when teaching. *Characteristic to moderate* refers to what on-going element of students' experiences during class the learning assistant feels they must attend to and keep within certain bounds. The preliminary themes were restructured in this way because these themes better described the underlying features that emerged from the data. While the preliminary themes attended to the surface commonalities among the learning assistants' comments, focusing on the content of their statements, the themes shown in Tables 3.6, 3.7, and 3.8 are better grounded in the substantive differences in the levels of considerations the learning assistants' discussed.

The next preliminary themes analyzed were the *purpose of computation* theme, because it was hypothesized that a learning assistant's perception of the usefulness of computation would have a notable effect on their teaching, and the *student frustration* theme because it was suspected that it may be accounted for already by the *student attitudes* variation of the *characteristic to moderate* theme. This was found to be largely correct, and the majority of the portions of transcript in the *student frustration* theme not identified as *student attitudes* were nonetheless accounted for by variations within the already identified themes. The variations ultimately identified within the *purpose of computation* theme appear in Table 3.9, retitled as *utility of computation*.

3.5.4 Development of categories of description

The final steps of developing the four themes presented thus far were informed by developing preliminary categories of description. The goal of a phenomenographic study is to develop categories of description that capture the different ways individuals may experience the phenomenon of interest [54, 137, 158, 159]. With this goal in mind, we considered the variations seen in the themes analyzed thus far. This was done at this point in analysis because

Utility of Computation Variations	
Variation	Description
Programming is an important skill	programming is a significant part of modern society
Computation aids content learning	computation helps students better understand physics concepts
Computation makes difficult problems easier	computation is valuable in modeling and solving complex problems
Computation offers space for broader skills	computation provides opportunities to develop skills valuable beyond the classroom and computation

Table 3.9: Variations within the *utility of computation* theme, describing what learning assistants perceive the usefulness of computation to be

the preliminary themes analyzed thus far indicated a rich variation in experiences teaching computational problems and provided a great deal of information with which to develop preliminary categories of description. Furthermore, the data analyzed thus far represented a great majority of the reduced data set to be considered. Based on these considerations, it was decided that it was an appropriate point at which to begin developing categories of description by looking across themes. This stage of analysis constituted a secondary thematic analysis within the bounds of the already identified themes, where we now analyzed the variations for emergent threads that described coherent approaches to teaching computational problems, and a set of preliminary categories were developed. The development of these categories aided in the finalization of the themes and variations in Tables 3.6, 3.7, 3.8, and 3.9, which in turn informed the refinement of the categories of description. This mutually informative process is described in detail in Appendix A, and resulted in the categories of description presented in the Results section of this chapter.

Having arrived at a set of coherent categories of description, the final step in analysis was to review the remaining preliminary themes in Table 3.5 and confirm that they were accounted for within the four themes identified thus far, or that they could justifiably be neglected. Several of the remaining preliminary themes were already accounted for within the themes in Tables 3.6, 3.7, 3.8, and 3.9 upon closer analysis. Specifically, it became evident that some preliminary themes had emerged based on characteristics that were superficial in light of the deeper themes and categories that had developed. The *written feedback*, *varying levels of student programming experience*, *acceptable places to end computation days*,*minimally working programs*, *solution manuals*, and *teaching challenges* themes were largely already described by the themes in Tables 3.6, 3.7, 3.8, and 3.9. A majority of the portions of transcript that had initially been sorted into these preliminary themes were determined to be simply context-specific discussions of learning assistants' teaching. An example appears in the quote below,

> [Using minimally working programs] impacts my teaching a lot because I feel like I only really focus on the things I teach them how to code, like understand the code, or more like the while loops. I teach them about what's already there and it's not like I'm starting like this is what code is, and this is how you code things, like a coding class would teach you. And so you can focus specifically on while loops and if statements, which really limits the amount of coding you're necessarily teaching them and you can focus more on the physics side of it.

While this learning assistant discusses minimally working programs in this excerpt, he ultimately is discussing that he seeks to avoid programming becoming a distraction. He emphasizes how he teaches computational elements like while loops and if statements, but does not get into the details of programming "like a coding class would". In this way, he expresses an attention to ensuring that those details do not become the students' focus. Thus, this excerpt is accounted for within the *characteristic to moderate* theme, specifically the *student attention to programming details* variation. The majority of the transcript sorted into the aforementioned preliminary themes was similarly better captured by the final themes.

Other preliminary themes were eliminated because they were found to not be central to our phenomenon of interest: learning assistants' approaches to teaching computational problems. The *different student approaches to computation*, *differences in student behavior solving computation versus analytic problems*, *what students should do when solving computation problems*, *why code in groups*, and *student challenges* themes were neglected because upon closer analysis, it was observed that while they did relate to learning assistants' perceptions of the computational problems, they did not provide insight into their approaches to teaching. In the *student challenges*, *different student approaches to computation*, and *differences in student behavior solving computation versus analytic problems* themes, learning assistants simply shared their observations of students, but did not connect these observations to their teaching. In the *why code in groups* theme (and the portions of the *written feedback*, *varying levels of student programming experience*, *minimally working programs*, and *solution manuals* themes that were not already accounted for by the final themes), learning assistants shared their opinions on the design of P Cubed, but again, did not connect these opinions to their teaching and did not elaborate sufficiently for their comments to give insight into their approach to teaching. In the *what students should do when solving computation problems* theme, learning assistants discussed the ideal problem-solving approach to computational problems, but did not describe why they held that belief or how it impacted their teaching. In all of these cases, interesting information about the learning assistants' perceptions of computational problems was revealed, but this information was not productive in describing their teaching approach.

For example, in the *student challenges* theme, one learning assistant discussed a problem that requires the students to model the motion of a rotating disk, in which the given code defines the y-axis to be the axis of rotation. She notes that this causes confusion for the students, because in analytic problems, the z-axis is often taken to be the axis of rotation.

> I think, I mean like, I feel like they are going to get confused about anything new, but that one, I know there was a lot of confusion with the different things. There was an axis and the origin, and so I know I had discussions with both my groups about what those meant and think it's also confusing because it's like in the z-axis, but I think on the code it's on the y-axis, something like that. So, I don't know, all of those changes, kinda I think make those a little bit difficult to understand.

The learning assistant's discussion of how students struggle with coordinate systems in the computational problems gives some insight into her opinions on computational problems and the students, but it does not give insight into how she approaches her teaching overall. While she does state that she "had discussions" with her groups about this particular issue, it doesn't reveal her *teaching strategy* or *teaching outcome*, and it doesn't give information that is helpful in identifying the variations in learning assistants' teaching approaches.

Having thus confirmed that the themes and variations in Tables 3.6, 3.7, 3.8, and 3.9 were sufficient to meaningfully describe the learning assistants' experiences as they related to their teaching approaches, and that cohesive categories of description based on groupings of variations within them could be developed (described in the Results section), analysis was concluded.

3.5.5 Validation

In addition to the processes described here, results were subject to validation throughout analysis and upon completion. The entire analysis process was conducted in regular consultation with a researcher with expertise in phenomenography. All analysis decisions were subject to scrutiny and discussion, and had to be adequately justified through evidence from the transcript and defensible arguments. This included decisions to merge themes or variations, eliminate themes or variations, and especially decisions on the final groupings of variations defining each category of description. In addition to this on-going validation, at several intermediate points in analysis, preliminary results were presented to external groups for critique and feedback. Finally, upon the conclusion of analysis, the final results, the interview transcripts, and examples of coded transcript were provided to another researcher for external validation of the results. Based on the evidence and arguments provided in this Chapter and in Appendix A, and the validation of these external researchers, we argue that the results presented in the following section constitute a novel and legitimate phenomenographic result that gives meaningful and useful insight into learning assistants' approaches to teaching computational problems.

3.6 Results

3.6.1 Categories of description

In phenomenographic studies, the categories of description are formed by looking across the themes identified in the data, seeking to identify groupings of variations that describe a cohesive way to experience the phenomenon of interest [54, 137, 158, 159]. Four categories of description capturing the differences in learning assistants' approaches to teaching computational problems were developed based on our data. They are summarized in Table 3.10 based on the variations that compose them, and are described in detail in the following section.

Category of Description	Utility of Computation	Teaching Outcome	Characteristic to Moderate	Teaching Strategy
Narrow programming focus	Programming is an important skill	Programming skills	Student work pace	Focus on navigating programming errors
Learning physics via computation focus	Computation aids content learning	Physics-code connection	Impact of course design	Leverage affordances of computational problems
Computation as a tool focus	Computation makes difficult problems easier	Capabilities of computation	Student attention to programming details	Encourage reflection on coding
Shifting perceptions of learning focus	Computation offers space for broader skills	A new approach to learning	Student attitudes	Leverage collaboration

Table 3.10: Final categories of description. The *narrow programming focus* treats the computational problems as a way to develop students' abilities to write code. The *learning physics via computation focus* treats the computational problems primarily as a means for learning physics concepts. The *computation as a tool focus* treats the computational problems as a way to help students understand the value of computation in modeling and solving problems. The *shifting perceptions of learning focus* treats the computational problems as opportunities to develop students' understandings of their own learning.

3.6.1.1 Narrow programming focus

The *narrow programming focus* category is based around an emphasis on computation as the act of entering code. There is little reflection on how computation may be used in teaching or science, rather it is treated as a valuable but unconnected skill.

In the *utility of computation* theme, it is characterized by the belief that *programming is an important skill* to have in today's society, with very little elaboration or explicit reflection on why this is. For example, one learning assistant said,

> [Programming] has been really helpful in a lot of my different classes, and then also in my internship this last summer, just like as an engineering person in general. That's one thing that I try and stress to the students, is it's like, "Okay, you might think that you're never going to use this, but it's actually so helpful if you do know how to use even just a small portion of it."

In this quote, the learning assistant describes how she tries to convey to her students that programming is helpful, noting that she has used it in multiple contexts. She discusses how she has used it inside and outside of the classroom, and references her background as an engineer. She does not elaborate on its importance in her learning or work, however, and she does not describe how or why it is helpful. Instead, she only states that students are likely to encounter it in other situations and that it can help them. This lack of reflection on *how* computation is helpful and relevant is an example of a learning assistant expressing a perception that the utility of computation is simply that *programming is an important skill*.

In the *teaching outcome* theme, the narrow programming focus is characterized by an emphasis on *programming skills*. That is, the learning assistant desires their students to gain an understanding of how to carry out programming tasks. One learning assistant said,

> If it's something where they added an object, or they were talking about an object, or coded in an object in their calculation loop, but never defined that object, then that's a place where it's like, "Okay, let's kind of go through this more line by line. What is this line telling us? Okay, where else does that object show up in the code? Wait, it doesn't show up anywhere else? We might need to address that." Because that is an understanding thing where they need to understand that they have to define something in the code before they can do anything to that object. You can't do something to an object that you don't have.

In this quote, the learning assistant discusses students facing an error resulting from referencing an object that they had not yet defined in their code, and states that is an error that she will intentionally target with her teaching. She goes on to say that she does this because the students "need to understand" the process of defining and calling objects in programming. Expressing a belief that her teaching should result in students knowing how to carry out elements of programming such as this indicates that *programming skills* are her desired teaching outcome.

In the *characteristic to moderate* theme, the *narrow programming focus* is characterized by *student work pace*. When moderating this characteristic, learning assistants attend to their students' rate of progress, seeking to ensure that students reach the end of the problem by the end of class. An example of this is given by a learning assistant who said,

> I might let them just mess with it for awhile. But it's sort of a time balance thing. So I've done these problems so many times, I know where they should be at certain times to make sure they finish, and so I usually let them mess with it until I think, "Okay, it's halfway through, they should be at this point. I'm gonna try to redirect them back to where they should be."

With this quote, the learning assistant indicates that regardless of the exploration she'll sometimes allow her students to do, she will take steps to ensure that they are able to finish the problem in the allotted time. She explicitly comments on using particular time markers to check on where students should be at different points in the class session. This emphasis on making sure students complete the problem indicates that she moderates *students' work pace*.

In the *teaching strategy theme*, the *narrow programming focus* is characterized by a focus on *navigating programming errors*. With this strategy, learning assistants focus their teaching on helping students identify and overcome programming errors in the traditional sense. That is, mistakes in their code that cause it not to function. One learning assistant employing this strategy stated,

> Most of the time, I just teach them how to do it because it's usually when they've just like edited like one line of code, and then it's like, "Oh, we have the tabbing error." I'll just be like, "Here's how you solve that: Highlight, and then do the thing, and then, yay, it's good." Then they'll be like, "Okay. Cool. Now I know how to do this in the future."

In this quote, the learning assistant describes a common error the students encounter: problems with their indentation. She explains that she tailors her teaching to this fact by preemptively instructing students on how to resolve that error. This emphasis on helping students handle errors of this nature demonstrates a teaching strategy that is focused on *navigating programming errors*.

When considered together, one can see how these variations come together to form a cohesive approach to teaching computational problems, and one that is focused on a narrow view of programming. With the belief that computation is essentially entering programming syntax, it follows that a learning assistant's desired teaching outcome would be those sorts of programming skills. Similarly, it follows that a learning assistant with this approach would employ a teaching strategy focused on navigating programming errors, because those errors represent the fundamental obstacles of computation when one views computation to be correctly entering code. The *narrow programming focus* corresponds to a belief that the utility of computation is simply that programming is an important skill. This aligns with a narrow understanding of what programming is, because without understanding there to be deeper connections between computation and science or learning, the usefulness of computation in P Cubed would simply be that students learn how to program. Finally, this approach is completed by a learning assistant moderating the pace at which their students progress through the problem. This corresponds to a narrow view of programming focus because again, without a reflection on computation as a pedagogical tool or a problem-solving tool, and with programming being the act of entering code, the "game" that students must play on computational days becomes merely to get properly working code. With this belief in mind, it follows that a learning assistant would want to ensure that their students complete the problem and arrive at a correct solution. All four of these variations therefore come together to illustrate an approach to teaching computational problems characterized by a narrow programming focus.

3.6.1.2 Learning physics via computation focus

The *learning physics via computation focus* is characterized by an emphasis on the computational problems providing a pedagogical tool that learning assistants may leverage in their teaching. Computation is perceived primarily as useful in the classroom to help students learn concepts.

In the *utility of computation* theme, the *learning physics via computation focus* is characterized by the belief that the value of computational problems is that they *aid students' content learning*. One learning assistant expressing this belief said,

> The students get to see it represented so it's kind of like a reward almost for writing out the code. They think if I do this it changes this and it's beneficial to see how ... For example, we did a problem with drag. So, it's good to see how drag affects this and if we increase the coefficient it'll do this and this. It's a good way they can input information and immediately see the results of how the physics is applied.

In this quote, the learning assistant expresses that he believes the usefulness of the computational problems to be their ability to help students better understand the concepts. Specifically, he discusses how students can use the immediate feedback that computation can provide as a means to see the impact of the different physics concepts they are learning, in this case, drag. This type of emphasis indicates a belief in the utility of computation being that it can *aid students' content learning.*

In the *teaching outcome* theme, the *learning physics via computation focus* is characterized by an emphasis on the *physics-code connection.* This refers to a desire for students to see and understand how the code and visualizations involved in computation relate to the physics concepts highlighted in the course. In one example of this teaching outcome, a learning assistant said,

> Actually understanding what you're coding and making sure you can tie it back to the physics. Like I said when you do the position update formula, you should be able to understand that that comes from this kinematic equation. You should understand how it relates and how it should affect it.

In this quote, the learning assistant describes what she wants her students to learning from the computational problems. She discusses that the students should be able to understand how particular lines of codes, like the position update formula, relate back to the physics equations they are familiar with in algebraic form. With this, she expresses that she wishes her students to gain an understanding of the *physics-code connection.*

In the *characteristic to moderate* theme, the *learning physics via computation focus* is characterized by a focus on the *impact of course design*. Moderating this characteristic means attending to the particularities of the way P Cubed is taught and incorporates computation, and seeking to minimize the negative impact of their limitations. Examples include the fact that students must share one laptop, that not all necessary information is always provided in the problem statements, and the availability of the four quadrants whiteboard for work organization. A learning assistant discussed this, saying,

> We have to consider who's taking over the group, like typing in by themselves, or maybe if somebody ... Like, if people have taken turns, but somebody hasn't typed in yet, then we do have to take into account that the code is something they should work on specifically, like working together with the code.

In this quote, she discusses the impact of students needing to share a single computer while solving the computational problems, which require code to be entered into the computer. She notes how individuals will sometimes dominate a group and do all the coding, and how other individuals may never get a turn to enter the code themselves, and how that dynamic is something learning assistants must monitor and address in their teaching on the computation days. Thus in this quote, she expresses that she moderates the *impact of course design* on computational days.

In the *teaching strategy* theme, the *learning physics via computation focus* is characterized by *leveraging the affordances of computational problems*. This refers to a learning assistant utilizing aspects unique to computation days in their teaching. An example of leveraging such an aspect is discussed by a learning assistant who said,

> I'll be like, "it's acting this way, why is it acting that way?" And when the students realize that, that's not possible, I'll start questioning things that they're

> missing. And if they see what they're missing, then they try to add that into the problem. This, once again, goes into pseudo code, because if they see what they're missing, I usually tell them to write it out first, so that they don't make those errors.

In this quote, the learning assistant describes how he will encourage his students to write pseudocode when they encounter difficulties on computation days. By pseudocode, he is referring to an approximation of what the desired code is, not yet worrying about entirely correct syntax. He explains that he will have students write this almost-code out on their whiteboard when they are having trouble getting it to work in the computer. As pseudocode is an attempt at writing information in a way the computer will ultimately be able to understand, it is a construct uniquely relevant on computation days. In this way, this learning assistant discusses employing a teaching strategy which *leverages the affordances of the computational problems*.

Considering these four variations together, there is a coherent approach to teaching computational problems that emerges that is centered around a focus on computation as a means of learning physics. With this emphasis on computational problems as a pedagogical tool, it is consistent that a learning assistant would view the utility of computation to be its ability to aid students' content learning. It also follows that a learning assistant with this approach would employ teaching strategies which leverage the capabilities of computation, given that they focus on computational problems as a means for students to learn physics concepts. The desired teaching outcome in the *learning physics via computation focus* is an understanding of the physics-code connection, that is, an understanding of exactly how the computational work relates to the physics concepts being taught. It is unsurprising that a learning assistant with this approach would want their students to understand the physics-code connection, because they view the computational problems as fundamentally being a venue for students to learn the physics concepts. With that view, it is understandable that they would want their students to explicitly understand how the code and visualizations present in the computational problems are connected to the physics. Finally, the characteristic moderated in this approach is the impact of course design based. Because the *learning physics via computation focus* as a whole is very focused on computation as a pedagogical tool and is grounded in the context of education, it is consistent that a learning assistant with this approach would pay attention to the classroom in which they are teaching, particularly the limitations and affordances that it presents, resulting in a focus on moderating the impact of the course's design in their teaching. This combination of four variations together characterize an approach to teaching computational problems that focuses on students learning physics via computation.

3.6.1.3 Computation as a tool focus

The *computation as a tool focus* is an approach to teaching computational problems that emphasizes the usefulness of computation as a method of approaching problems. Computation is treated as a tool that is valuable in mathematical and scientific problem-solving.

In this *utility of computation* theme, the *computation as a tool focus* is characterized by the belief that *computation makes difficult problems easier*. It is a perception that computation provides affordances that are an important part of modeling or solving complex problems. One learning assistant expressing this belief said,

> What makes the computer good is that it involves ... Like a big thing is the time step. The smaller you make that time step, the more accurate everything is. If you wanted to write and draw that out, you could, but you'd have to use a grid system. You could. I don't know how much that would actually help or prove.

In this quote, the learning assistant discusses that computers can be used to carry out iterative numerical calculations, and that it is simple to control how many iterations the computer calculates by modifying the time step (the interval between each calculation). He contrasts that with how difficult it would be to do this analytically. He explicitly identifies the ability to do an increasing number of calculations easily as "what makes the computer good". By articulating and emphasizing how computation can be utilized to carry out difficult calculations, he indicates a belief that the utility of computation is that it *makes difficult problems easier.*

In the *teaching outcome* theme, the *computation as a tool focus* is characterized by an emphasis on students appreciating the *capabilities of computation.* With this outcome, a learning assistant wants their students to understand the benefits that computation provides. This is closely tied to the aforementioned belief that the *utility of computation* is that it *makes difficult problems easier.* While computation *making difficult problems easier* describes what the learning assistant perceives the usefulness of computation to be, the *capabilities of computation* describes what they want their students to takeaway from their experience with computation. An example of this appears from a learning assistant who said,

> The computation is important, it's an important skill, but understanding how the computation is helping them solve physics is always what I think about the most. The computer is solving all these equations and updating all this stuff, so what does that mean on pen and paper, and what does that mean for the physics?

In this quote, the learning assistant discusses how she focuses on how computation helps students solve the physics problems. She explicitly states how this is the important part of computation, and how it is more important than just the skill of being able to program. She expresses that what she wants students to understand how exactly it is that the computer is helping them. In this way, she suggests that the desired teaching outcome she has for her students is that they gain an understanding of the *capabilities of computation*.

In the *characteristic to moderate* theme, the *computation as a tool focus* is characterized by *student attention to programming details*. This means an attention to preventing students from becoming too caught up in the details of syntax and coding, to the detriment of their understanding the larger picture of computation. One learning assistant moderating this characteristic said,

> When it's just a spacing error that they've been working on for ten minutes, that's not super productive. And hopefully they just call me over when that happens, but I'm sure there are times when they're just messing with an error for 15 minutes, or ... probably not that long. Hopefully not to that point, but where they still have no idea how to fix it, and it's not helping them learn the physics, and it's not really helping them learn coding, 'cause they're just trying to find this tiny error.

In this quote, the learning assistant describes a difficulty students often have during the computational problems: getting their code properly spaced and tabbed. She discusses how spending too much time on this sort of error is not a good use of the students' time, explicitly noting that it does not help them learn the physics concepts *or* coding. She also expresses that she hopes she is able to intervene before the students waste too much time on a task like this. By treating the navigation of this sort of error as not aligned with learning coding and by indicating that she does not want students to spend time on these types of issues, she indicates a desire for students to not focus on unimportant programming details to the neglect of other computational skills. In this way, she expresses that *student attention to programming details* is a characteristic she moderates.

In the *teaching strategy* theme, the *computation as a tool focus* is characterized by *encouraging reflection on coding*. This means prompting students to think more deeply about how their code functions and how they can best utilize the program. A learning assistant discussing this strategy said,

> I would get them to focus on talking about how the code is supposed to be iterative. It's supposed to do the calculations for you. You shouldn't be doing the calculations outside of it and inputting numbers because then you're constraining the code to specific parameters, [but] the code is very versatile. You're supposed to be able to just hit run, change things to see how changing the variables affects the system.

In this quote, the learning assistant discusses how he will encourage his students to talk about what the code is able to do, such as carrying out calculations and allowing one to keep parameters variable. He emphasizes that the code is "very versatile" and that this should be leveraged, and he describes how he encourages his students to discuss these matters. This focus indicates a teaching strategy that is based on *encouraging students to reflect on coding*.

These four variations considered at once illustrate a coherent approach to teaching computational problems that is based around a focus on computation as a tool. Given a focus on computation as a tool, it follows that this teaching approach is characterized by a belief that the utility of computation is its ability to make difficult problems easier when leveraged, as this represents an example of its application as a tool. It also follows that a learning assistant with this approach would want their students to understand the capabilities of computation that make it such an important tool. In order to achieve this desired teaching outcome, it is consistent that a teaching strategy focused on encouraging reflection on coding would be employed. Prompting such reflection would facilitate students developing an appreciation for the affordances that computation provides them, and this emphasis makes sense given a focus on computation as a tool. The characteristic to moderate in this approach is student attention to programming details, which is also consistent with a belief that computation is a valuable tool. A learning assistant with this approach perceives computation to be more than simply entering syntax, instead treating computation as an important tool that can be utilized in modeling and solving difficult problems. Correspondingly, they do not wish their students to become bogged down in the details of syntax and leave with the impression that that is all that computation is. Rather, they want students to gain an appreciation of the greater value of computation. In this way, these four variations come together to indicate an approach to teaching computational problems that is focused on computation as a tool.

3.6.1.4 Shifting perceptions of learning focus

The *shifting perceptions of learning focus* is characterized by an emphasis on computational problems as an opportunity to affect students' beliefs about and approaches to learning. Computation is viewed as more than a pedagogical or problem-solving tool, and is instead treated as a means to impact students' ongoing ideas about how they learn and approach problems.

In the *utility of computation* theme, the *shifting perceptions of learning focus* is characterized by the belief that *computation offers a space for broader skills to be developed.* These skills could include how to collaborate effectively, how to think in new ways, and how to persevere through challenging problems. One learning assistant with such a belief said,

> That's [the computation problems] definitely where I see them learn a lot of effective ways to work in a group or in a team, which that's a big part of this class. Going forward, they definitely will need to know how to do that.

In this quote, the learning assistant describes how she has observed that the computation days are where the students most learn how to collaborate. She goes on to state that this is an important skill for them to know beyond the course. With this, she indicates a belief that the computational problems' utility is their ability to *offer students a space to develop broader skills* that go beyond physics and computation.

In the *teaching outcome* theme, the *shifting perceptions of learning focus* is characterized by *a new approach to learning.* This refers to a desire for students to develop a new approach to their learning through the computational problems. A learning assistant with this goal for their teaching said,

> I was trying to get them to see that, "Okay, if these two conditions are conflicting, then that statement will never be true, so that segment of code will never run." [...] If it's high up, then that just stops the code. Trying to get them to think through it logically rather than just like, "Okay, well let's just type something in and see if that changes anything," so stepping back and going, "Okay, well we know that this is true, we know this, and let's just look at this from a logical physics perspective rather than a coding perspective."

In this quote, the learning assistant describes a situation in which her students' code was not running because they had entered conflicting conditions. She explains how she wanted her students to think "logically" through the code and error, rather than simply making changes arbitrarily, demonstrating a desire she had for her students to take a more intentional and methodical approach to their problem-solving. This sort of focus on changing how students approach their learning and problem-solving is indicative of a new approach to learning to being her intended teaching outcome.

In the *characteristic to moderate* theme, the *shifting perceptions of learning focus* is characterized by *student attitudes.* When moderating this characteristic, a learning assistant focuses on ensuring that students do not become too frustrated or unhappy while working on the computational problems. A learning assistant moderating this characteristic with her teaching said,

> If they say something like "this is so frustrating, like I just want to give up," then you'll see them kind of start to get disengaged I guess. Like while you're doing the trial and error, usually the whole group is kind of looking at what's going on and is involved and wants to fix it and make it work. When you see them start to sort of you know, fall back and give up essentially then that's kind of where you want to make sure that you get them on the right track I guess.

In this quote, the learning assistant describes how she identifies when students have become frustrated to the point of no longer participating. She notes that at the beginning of problems, when groups are typically testing what different changes to the code do, students are generally engaged, but that as the problem progresses, frustration can lead to students becoming disengaged. She highlights that it is important to make sure that students do not get to that point of frustration. This focus on preventing students from becoming too demoralized indicates that she perceives *student attitudes* to be an important characteristic to moderate.

In the *teaching strategy* theme, the *shifting perceptions of learning focus* is characterized by *leveraging collaboration*. When employing this strategy, learning assistants capitalize on the fact that the course is a collaborative learning environment, and that students work in groups. One learning assistant discussing this teaching strategy said,

> I might say something like you know, ask somebody, ask a group what they are doing and if someone responds and it looks like the other two aren't paying any attention, I might ask, "Oh, are you guys good with that?" or like "Are you guys on the same page?" or "Do these guys understand that?" or something like that to sort of let them know that they should be conversing.

In this quote, the learning assistant describes how she will ask questions of a group that are targeted at assessing if there is agreement amongst the students and if all the students understand the group's work. She explains that she does this to convey to them that they should all be discussing the problem and concepts with each other as they work. This focus on encouraging students to take advantage of the fact that they are working in groups by having more discussions is an example of employing a teaching strategy that *leverages collaboration*.

In combination, these four variations describe an approach to teaching computational problems that is focused on computation as a way to shift students' perceptions of learning. With this view of computation in mind, it follows that the desired outcome of a learning assistant's teaching would be for students to adopt a new approach to their learning from the avenue for this that computation provides. It also is consistent that a learning assistant focused on computation as a way to shift learning perceptions would believe the utility of computation to be that it provides a space for students to develop skills that are beyond content. Skills like collaboration and intentionality when problem-solving are tied to how students' approach and perceive their learning, and so a learning assistant with a focus on shifting perceptions of learning would emphasis computation's utility in developing those skills. The *shifting perceptions of learning focus* is characterized by a teaching strategy that leverages collaboration. This strategy is also aligned with this focus because by leveraging collaboration, a learning assistant utilizes an aspect of the learning environment that is specifically designed to alter how students approach their learning and problem-solving. This strategy thus implicitly addresses how students approach their learning, and continues the focus on computation as a way to shift perceptions of learning. The characteristic to moderate corresponding to this approach is student attitudes. In order to attempt to shift students' perceptions of learning through the computational problems, it is unsurprising that a learning assistant would attend to student attitudes, and in particular, make sure students did not become frustrated to the point of disengagement. If a learning assistant is focused on shifting students' perceptions of learning, it is understandable that they would believe that engagement and a positive attitude are necessities to being able to influence students in this way. Thus these four variations when considered together comprise an approach to teaching computational problems that focuses on their ability to shift students' perceptions of learning.

These four categories of description capture the variation in how the learning assistants described their approaches to teaching computational problems in this environment. As described previously, however, categories of description are only part of the results of a phenomenographic study. The categories must also be connected via some logical structure known as an outcome space [54, 137, 158, 159]. The outcome space relating the categories presented in this study is described next.

3.6.2 Outcome space

The four approaches to teaching computational problems identified in this study are connected in a hierarchical structure, shown in Figure 3.1. Going from the *narrow programming focus* to the *shifting perceptions of learning focus*, each approach represents an increasing level of sophistication. While sophistication may be defined in many ways, here we take a sophisticated approach to teaching to be one that indicates greater reflection on the purpose of one's teaching and students' learning.

With the *narrow programming focus*, computation is treated primarily as a means to learn programming skills, such as syntax and elements like loops. These skills are not framed as being connected to students' learning or their perceptions of computation or learning, and instead are treated as things that are simply good to know with little reflection on why. By neglecting to reflect in this way on what computation is and what it offers students, such an approach indicates a relatively unsophisticated understanding of the purpose and usefulness

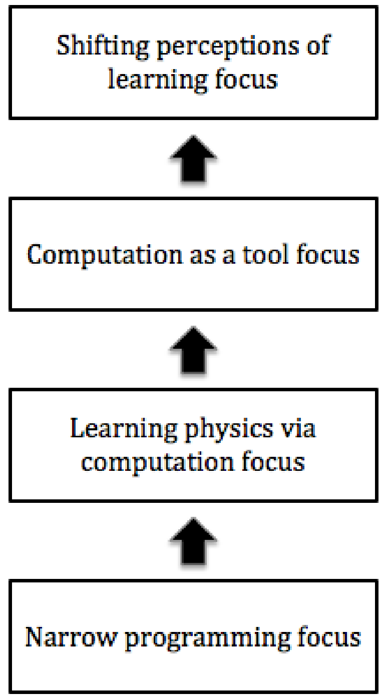

Figure 3.1: Outcome space indicating the hierarchical structure relating the identified learning assistant approaches to teaching computational problems

of teaching computational problems in the course, and a very narrow goal for one's teaching.

In the *learning physics via computation focus*, the computational problems are treated as pedagogical tools. They are framed as contexts that offer particular opportunities to develop students' understandings of the physics concepts. This approach is more sophisticated than the *narrow programming focus* because it indicates some reflection on the ways that the computational problems can aid students' learning beyond simply gaining programming proficiency. It demonstrates an attention to the fact that the computational problems are about physics concepts and are embedded in a physics course, and an intentionality about leveraging that in one's teaching. This approach does not expand beyond the classroom or the course's subject, however, to consider the broader value and opportunities the computational problems provide.

The *computation as a tool focus* represents such an expanded focus, by treating the computational problems as an opportunity for students to better understand the value of computation outside of the classroom. Rather than seeing computation as a mechanism to help students understand the physics concepts that they are meant to learn in the course, the computational problems are framed as a space for students to gain an appreciation of the power of computation in solving complex problems. This approach indicates an increased level of sophistication from the *learning physics via computation focus* because it goes beyond the physics content the course explicitly addresses, and attends to the impact that the computational problems can have on students' perceptions of computation itself. As the context of this study was a physics course, it is to some degree a given that developing students' understanding of physics is a central part of teaching the course. Because of this, taking an approach to teaching that is centered around the learning of physics is not as indicative of additional personal reflection as taking an approach that goes beyond the course's explicit subject matter. The *computation as a tool focus* represents an approach that indicates such additional reflection.

The *shifting perceptions of learning focus* is more sophisticated still, as it treats the computational problems as a venue in which to impact students' perceptions of and approaches to their own thinking, learning, and problem-solving. Rather than focusing on the classroom-style learning of physics concepts or even students' general perceptions of computation, this approach frames the computational problems as a chance to alter how students go about learning new things regardless of the context. This represents the most sophisticated approach of the four, as it aims to make a lasting change in how students approach problems beyond the bounds of the classroom and computation.

In this way, the four approaches to teaching computational problems identified through the learning assistants in this study represent an increasing level of sophistication of approach. Progressing up Figure 3.1, each approach indicates learning assistants engaging in deeper reflection on and possessing a broader understanding of how they might utilize the computational problems in their teaching. In the next section, we will discuss the meaning and implications of the approaches identified in this study and the hierarchical structure relating them.

3.7 Discussion

There were four themes that were salient when considering the teaching approaches the learning assistants interviewed for this study took to teaching computational problems: their perceptions of the utility of computation, their intended outcome for their students, what characteristics they moderated while teaching, and the strategies they employed while teaching. Based on learning assistants' beliefs about each of these themes, we identified four approaches to teaching computational problems: a narrow focus on the act of programming, a focus on learning concepts through computation, a focus on computation's position as a valuable tool, and a focus on shifting students' perceptions of their own learning. Each of these approaches represents an increasing level of sophistication in approach to teaching, and furthermore, indicates varying degrees of alignment with goals of the course design of P Cubed. In its intended design, P Cubed does not emphasize the acquisition of simple programming skills as a goal, and thus the *narrow programming focus* is not very aligned with course goals. Naturally as a physics course, developing students' conceptual understanding of physics is an intended outcome of P Cubed, and the *learning physics via computation focus* is in line with this. P Cubed has intended outcomes for students beyond conceptual understanding, however. It is a goal of the course to frame computation as a valuable skill and tool in approaching problems, and to encourage students to reflect on their learning, problem-solving, and collaboration [32]. These goals appear in the two most sophisticated approaches identified: the *computation as a tool focus* and *shifting perceptions of learning focus*. The approaches to teaching computational problems that we identified are therefore not entirely surprising, as they suggest learning assistants are taking up different goals of the course to different degrees.

As described previously, the learning assistants interviewed for this study came from diverse majors and backgrounds with respect to computation and teaching, and also had varying levels of experience teaching in P Cubed. This led us to believe we would uncover meaningful variations in their approaches, and the development of the categories of description and outcome space presented here confirms that this was the case. After developing these results, the interview of each learning assistant was considered individually, in order to identify with which approach to teaching each was most aligned. An individual's transcript was examined for comments regarding each theme, and for which variation within each theme these comments reflected. Based the variations an individual most reflected in each theme, they were assigned to the teaching approach that was most aligned with their combination of variations. Because the teaching approaches identified in this study were not developed with the aim of unambiguously categorizing these learning assistants, most individuals did not align perfectly with a single teaching approach, and instead expressed elements of multiple teaching approaches. Learning assistants were therefore assigned to a teaching approach based on the one that best accounted for the variations they expressed in each theme. Table 3.11 shows the number of learning assistants aligned most with each approach, and the number of semesters that each had taught in P Cubed.

Teaching approach	Number	Experience levels
Narrow programming focus	1	5 semesters
Learning physics via computation focus	4	1, 2, 3, and 3 semesters
Computation as a tool focus	1	6 semesters
Shifting perceptions of learning focus	6	1, 2, 2, 4, 4, and 5 semesters

Table 3.11: Number of learning assistants with each teaching approach and their experience levels

The results of this sorting are interesting for several reasons. First, the majority of the learning assistants take either the *learning physics via computation focus* or the *shifting perceptions of learning focus*. These two approaches have less explicit focus on computation than the *narrow programming focus* and *computation as a tool focus* themes, perhaps indicating that learning assistants are likely to view the computation as secondary to learning, whether it be conceptual learning or reflection on learning. Another notable result is that there does not appear to be a correlation between amount of experience and teaching approach. The two most populated approaches had comparable distributions of experience, and the only learning assistant with the least sophisticated approach was one of the most experienced, with five semesters of experience. This result suggests that it is unclear what effect experience in the classroom has on the teaching approaches that learning assistants take. Investigating the teaching approaches that learning assistants discuss over the course of their tenure, or before and after training could shed light on what causes shifts in their approaches. Using the teaching approaches identified here as a lens to consider the changes or lack of changes in their approaches could inform for how we train and support the development of our learning assistants as teachers. For example, the pre-semester training currently does not discuss the computational problems or their purpose explicitly, and modifying the training to address this could encourage learning assistants to adopt the more sophisticated approaches. Doing this could ensure that the intended course goals and messages regarding computation are reaching the students. We also investigated if there were correlations between the approaches learning assistants took and their major, class rank, or gender, and found no correlations.

The increasingly sophisticated approaches to teaching presented here have connections to previous research on approaches to learning, and previous research on instructors' beliefs and practices in teaching [87, 98, 100, 153, 170–172]. Several studies in particular have notable connections to our results.

In their work on learning assistants' beliefs about teaching and learning, Gray et al. examined a context that did not involve computational problems, but their results have a relationship with ours nonetheless. They found that learning assistants may perceive themselves as occupying four different roles: facilitating physics content, facilitating students' sense-making, shaping the learning environment, and professional growth [87]. The first two roles identified in their work are aligned with the *learning physics via computation focus*, in that they frame physics content in some way as the primary goal. Their identification of two versions of a focus on physics content could be related their context, in which students work primarily on tutorials. Tutorials are structured and ask direct questions, which could prompt learning assistants to engage in simple content transmission so that students arrive at those answers. The problem-based learning style of P Cubed might make such an approach difficult to implement, since students must navigate complex problems that may not have clearly defined questions. As a result, it's possible the *learning physics via computation focus* identified here is more comparable to their facilitating students' sense-making role. The shaping the learning environment role they identified may be related to the *shifting perceptions of learning focus*, as both contain a focus on the collaborative nature of the learning environments. In the shaping the learning environment role, however, it is not clear if the learning assistants want their students to adopt a new learning style as in the *shifting perceptions of learning focus*, or if they simply see themselves as a moderator of group dynamics. The professional growth role identified by Gray et al. did not appear in our data. This could be because we did not probe this area of their experiences in our interviews, and it could also be because the P Cubed learning assistant model does not explicitly emphasize its role in the development of new teachers in the way that the University of Colorado Boulder (where Gray et al. conducted their work) learning assistant model does [84].

Our results are also related to the work by Bruce et al. on students' experiences learning programming. Although they focused on student experiences, and the work presented here focuses on instructor approaches, parallels can be seen between the results of each. In their phenomenographic study, Bruce et al. identified five experiences that students may have with respect to programming: following, coding, understanding and integrating, problem-solving, and participating, with each representing a student taking on a more expansive view of programming[153]. Both the "following" and "coding" categories are related to the *narrow programming focus*, as they all focus on simply accomplishing the computational task and gaining some degree of proficiency with writing code. The "problem solving" category is aligned with the *computation as a tool focus*, as both treat programming as a way to approach problems. Because their work was carried out in a context explicitly teaching programming, while ours was carried out in a physics course which incorporated programming, other connections between the results are less clear. The "understanding and integrating" category may be related to the *learning physics via computation focus* as both focus on gaining a conceptual understanding of the course's content, whether it be programming itself or physics. The "participating" category may be related to the *shifting perceptions of learning focus*, as both describe a broader change in how students perceive their work, gaining an understanding of programming as a community in the case of the former, and gaining an understanding of a new approach to learning in the latter. While the relationship between our results and those of Bruce et al. is not entirely clear, these connections could provide some insight into how learning assistants come to their teaching approaches. Because learning assistants experience the class first as students themselves, and because little time passes between their experiences as students and their experiences as instructors, it could be that their student experiences are having a significant impact on their teaching approaches.

The results presented here are closely related to the phenomenographic study by Magana et al. on instructors' intended outcomes when teaching computation. They found eight different intended outcomes that instructors may have in incorporating computation into their courses: to become aware of the role of computation in science, to make measurements, to find causal relationships in models, to test models, to validate results, to use computational techniques, to predict behavior, and to discriminate among possible models. They further argued that these eight intended outcomes represent increasingly higher order levels of thinking [100]. It is difficult to match these to our results precisely, since their results describe desired outcomes, which is just one of the four themes that comprise each of the teaching approaches identified in our work. Despite this, there are relationships that can be uncovered. The "become aware of the role of computation in science" outcome is aligned with the *computation as a tool focus*, as both emphasize students gaining an understanding of the usefulness of computation. The "use computational techniques" outcome is aligned with the *narrow programming focus* in that both emphasize students gaining programming skills. It is difficult to determine how their remaining identified outcomes relate to the teaching approaches we identified. It could be that the instructors they interviewed have these intended outcomes towards the goal of students better understanding the concepts of their scientific discipline, which could align with the *learning physics via computation focus.* It could also be that they have these intended outcomes towards the goal of showing students specific computational capabilities, which could align with the *computation as a tool focus.* None of the intended outcomes identified by Magana et al. appear to have an explicit relationship to the *shifting perceptions of learning focus.* It's also worth noting that their hierarchy of instructors' intended outcomes based on higher orders of thinking does not align with our hierarchy based on increasing levels of sophistication in approach. For example, while they position "become aware of the role of computation in science" as the lowest order level of thinking, we position the *computation as a tool focus* as one of the more sophisticated approaches to teaching. These seemingly contradictory rankings may be a result of our teaching approaches being described by elements beyond the learning assistants' desired outcomes that when considered together, provide a picture of an approach that has more sophistication.

There are limitations to our results. The approaches to teaching computation identified here are based on learning assistants teaching in a problem-based course, and one that puts significant time and effort into their training. Additionally, the course implements computational problems in an intentional way and has particular goals for students' engagement with those problems. This likely affected the experiences the learning assistants discussed and the approaches to teaching that they adopted. Indeed, as previously described, the approaches identified here are closely related to the course's intended goals, and it is possible that in a course emphasizing different goals or implementing computation differently, different teaching approaches may be identified. A different set of learning assistants could discuss new themes that were not present in these interviews, and they could also discuss the themes identified here in different ways, resulting in new variations. Because of this, the themes and variations upon which the approaches to teaching identified here were built do not account for all learning assistant experiences, though our results still provide a framework that would be useful when examining the experiences of new populations. For example, Michigan State University now offers a degree in computational mathematics, science, and engineering, and it is possible that a learning assistant from that program would have unique ideas about the purpose of computation instruction in a science course. We have had no learning assistants yet from this major, but if any do join the teaching team, it would be interesting to compare their comments to the approaches found here. The themes and variations identified here also do not fully describe the experiences of the learning assistants in our context. As a method, phenomenography seeks to build the most concise categories that capture the variations uncovered in the experiences of the participants. This means that not every element of each participant's experience is captured in the categories, because it is the crucial variations in experiences that are the focus of analysis. While this does result in the loss of some of the nuance in each individual's experience, it is also what lends phenomenography its strength as a method for finding commonalities and variations in the experiences of a collective. It is worth noting that phenomenographic studies typically use sample sizes of 15-20 participants [169], and that 12 learning assistants were interviewed for this study. While we do not believe that interviewing more learning assistants from P Cubed would drastically change our results, it is possible that such additional data could provide some refinement.

Despite these limitations, the work presented here provides valuable insight into learning assistants' experiences teaching computation. The identification of the increasingly sophisticated teaching approaches identified here provides a framework that can be used to understand what course goals our learning assistants are taking up, and could also be applied to investigate how their approaches develop over time or to determine if similar teaching approaches emerge in other contexts. As more physics courses incorporate computational problems into their curricula, and as more courses shift towards collaborative learning environments that may require teaching to be delegated to learning assistants, it will be important to understand the approaches that instructors take to teaching in these environments. Better understanding these approaches and how to influence them can allow us to best support instructors as they facilitate students' learning in these complex environments.

Chapter 4

Identification of a shared answer-making epistemic game in a group context

The following chapter was published in the proceedings of the 2015 Physics Education Research Conference [56], and is presented here with minor modifications from its appearance in publication. It was published with second and third authors Paul W. Irving and Marcos D. Caballero.

4.1 Abstract

When physics students engage in collaborative exercises, they must negotiate their different problem-solving strategies in order to work together effectively. One lens through which to understand these interactions is the construct of "epistemic games". These constructs have been used to describe particular methods of problem solving with which students are observed to engage. In prior work, an "answer-making epistemic game" has been observed, wherein the student perceives the objective of the activity as producing an answer, and reasons until they arrive at an answer or intuits an answer and then tries to justify this answer. This game

was observed in the context of individual students working independently on multiple-choice questions. We present the identification of a shared answer-making epistemic game when a group of students worked collaboratively on conceptual problems.

4.2 Introduction

The use of collaborative work is becoming increasingly prevalent in introductory physics classrooms. In such environments, students must engage with not only physics content, but also with their peers and their peers' understanding of physics content and problem-solving strategies. In order to best provide learning opportunities, it is essential to understand how students interact in such environments. To this end, the construct of epistemic games has been used as a productive lens through which to analyze students' behavior when problem-solving [27–29]. An epistemic game is defined by Tuminaro and Redish as "a coherent activity that uses particular kinds of knowledge and processes associated with that knowledge to create knowledge or solve a problem" [28].

The answer-making epistemic game (AMEG) is relevant to the work presented here [29]. In this game, a student works under the belief that the objective of the activity is to produce a solution. The AMEG begins with students engaging in the entry condition of attempting to remember the answer to the question on which they are working. If they cannot remember an answer, they will attempt to intuit an answer. At this point, students will enter one of two possible paths consisting of different series of moves. If the student can intuit an answer, they will accept this answer, and then attempt to use conceptual reasoning or do math in order to arrive at a justification for the answer (the "answer justify" path, AJ). If a student cannot intuit an answer, they will reason conceptually or do math until they arrive at an answer (the “reason answer” path, RA). Both paths are defined by the same exit condition: a solution that the student finds to be sufficient. These series of moves and entry and exit conditions describe the structure of the AMEG. The AMEG is further defined by an ontology comprised of its epistemic form, a truth table, and its knowledge base, the physics and mathematical resources that students activate as they engage with the game.

The AMEG was studied in the context of think-aloud interview protocols carried out with individual students working on multiple-choice hydrostatics questions. In this paper, we identify via a case study a shared answer-making epistemic game (SAMEG) in a group context in which four students worked together on a conceptual electricity and magnetism (E&M) problem. The students in this group were observed to engage with the activity in ways that appeared similar to the AMEG, but that could not be fully accounted for by that epistemic game. The model of the SAMEG was developed in order to attempt to describe more fully the behavior of this group. As such, we do not propose the prevalence of the SAMEG, and instead only present its existence through the case study of this group.

4.3 Study context

The data presented in this paper was collected from an introductory E&M course at a large university. There were approximately 120 students in the course, and most were sophomore life-science majors. The students all attended lecture three times a week, and a laboratory session once a week in sections of approximately 20 students. In these laboratory sessions, students worked in groups of three or four collaboratively on a variety of activities depending on the week (labs, tutorials, conceptual and calculational problems, etc.). The data presented here are transcripts from video recorded of one group of four students working during their

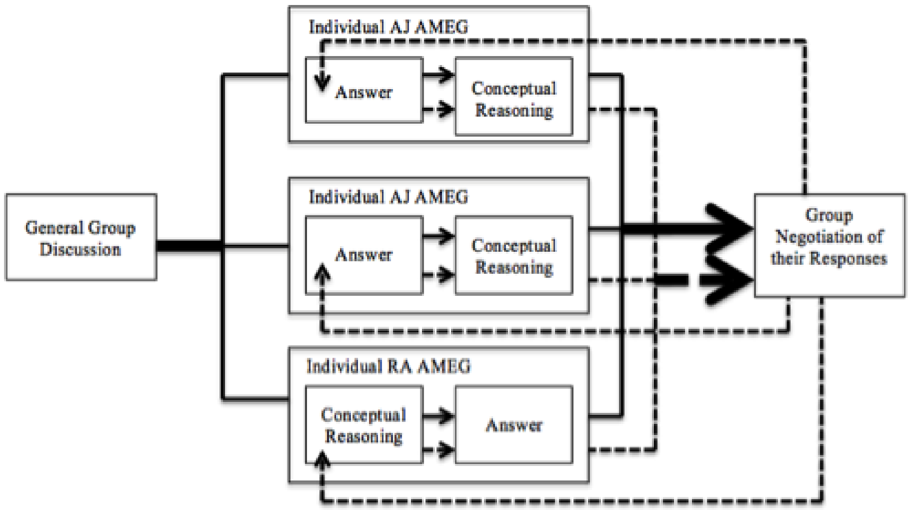

Figure 4.1: A schematic of the shared answer-making epistemic game showing how students progress through the game

weekly laboratory section. In the episode, the students are attempting to identify if there is a point of equilibrium in the space surrounding an electric quadrupole, and if so, where that point is. They do so by examining an image of the space surrounding the charges as represented by electric field vectors. It is worth noting that the students are not told that such a configuration of charges is called a quadrupole, and that they had not seen such a configuration previously in class. The students in question have been given the pseudonyms Buster, George, Lindsay, and Michael. The data will specifically regard George, Lindsay, and Michael, as Buster quickly disengages with the activity. He leans back from the table, does not speak, and does not often look at the students who are speaking.

4.4 Shared answer-making epistemic game

As illustrated in Figure 4.1, three students participated in the SAMEG, while one was not observed to participate. In these observations, the SAMEG was characterized first by an entry condition, general group discussion. After entering the SAMEG, the participating students played the original AMEG individually. One student played RA, while the other two students played AJ. After the participating students exited their individual AMEGs, they engaged in a group negotiation of their responses. The first time they attempted this, they were unsuccessful, and so the their next moves were to return to their individual AMEGs (dashed lines in Figure 4.1). The participating students played their individual AMEGs a second time, exited them, and then again attempted a group negotiation of their responses. This time they were successful, and so they exited the game. The exit condition was thus all participating students being simultaneously satisfied with their individual solutions and also having successfully navigated a group negotiation of their responses. We detail the components of the SAMEG below, providing evidence from video data of the four aforementioned students working on this problem.

4.4.1 Entry condition

The participating students began playing the SAMEG through the entry condition of a general group discussion. All four students' first actions were to discuss together what the problem was asking of them and to begin proposing ideas. The students were observed to lean over the image and speak in approximately equal amounts about the image. No answers were put forth, and no student offered reasoning directly leading to producing an answer. This stands in contrast to the original AMEG, which is characterized by the entry condition of remembering or intuiting an answer [29]. By the nature of the problems these students were asked (i.e., the students had never seen the given charge distributions), remembering was unlikely to occur and was not observed. Intuiting answers was also not observed to be any of these students' first actions.

As they begin working, all four students leaned in towards the image at the same time, and began gesturing simultaneously. They took turns identifying charges (00:02-00:18),

> Michael: So clearly, right here is a negative.
>
> George: [Pointing at another charge] Positive.
>
> Lindsay: [Pointing at different charge] This is positive.

By the student responses, we can interpret that no student remembers or intuits an answer to the problem, and no student reasons conceptually in a way that is directly related to answering the problem. Instead, the students are speaking in equal amounts about the problem; trying to understand the image they have received – a general group discussion.

4.4.2 Individual AMEGs

After the students entered the SAMEG by engaging in the entry condition, they entered a sequence of particular moves. In the first of these moves, the students were observed to play the original AMEG on an individual basis (thin solid lines in Figure 4.1). During this time, the students still spoke and responded to each other while they engaged independently in the AMEG. The intuit, answer, conceptual reasoning, and sufficient solution moves were all present. These moves were observed in the context of individual students playing the RA or AJ paths.

It is at this point in the episode that one student, Buster, disengaged from the group. He leaned back in his seat, and did not speak until the very end of the group's work on the problem. Two students, Lindsay and George, played the AJ game by first intuiting answers, then using conceptual reasoning until they found their solutions sufficient. Having not provided any explicit reasoning first, Lindsay points at the image (00:23-00:29) and says,

> Lindsay: So this is the place right where you could put the charge. Because these [electric field vectors] cancel.

Similarly, at (00:25), George agrees with Lindsay's answer without explicitly demonstrating conceptual reasoning first. Instead, it is after affirming an answer that he reasons (00:36-00:38),

> George: It's like tic-tac-toe.

where it is interpreted that he is referring to the electric field vectors. The third student, Michael, played the RA game by using conceptual reasoning first until arriving at an answer comprising a solution he found sufficient. While leaning over the image (00:30-00:36) he says,

> Michael: [Pointing at electric field vectors] One in, one out, one in, one out. [Now pointing at center of quadrupole] Yeah.

He then leans away from the image and begins to write on his worksheet.

The presence of both the RA and AJ paths suggests this portion of the students' behavior was in fact an individual playing of the original AMEG. They approached the problem in different ways, independent of one another's choice of pathway. Furthermore, the students did not progress through the moves of the original AMEG at the same rate and did not arrive at sufficient solutions simultaneously. Lindsay found her solution sufficient first at (00:31), followed by Michael at (00:36), followed by George at (00:39), as determined by the point at which students stopped speaking and began writing on their worksheets. This also points to the students playing the AMEG as an individual activity, because they determined the sufficiency of their answers on an individual basis.

4.4.3 Group negotiation of their responses

In the SAMEG, once all participating students in the group completed playing their individual AMEGs, they engaged in a group negotiation of their responses. In this negotiation, students discussed their individual solutions in an attempt to agree upon a final response to the problem that all group members found acceptable. They did not seek to agree upon the specific wording of a response. Instead they assessed first whether each student had a solution that she personally found sufficient, and then that no individuals' solutions were contradictory. The students in this group were observed to carry out a group negotiation of their responses twice (described further in the next section). The data in this section will regard the group's second, and successful, attempt at this negotiation (thick dashed line in Figure 4.1).

After the students (except Buster, who continues to not engage with the group) complete their second passes through the original AMEG, Lindsay asks Michael (04:10-04:15),

> Lindsay: [addressing Michael] So you're saying it's going to be between two...
>
> Michael: Either two negatives or two positives.

At this point, Lindsay begins writing – an action that we have used to indicate that she finds her solution sufficient. Michael and George continue discussion (05:30-05:48),

> Michael: It's two like charges will cancel each other out.
>
> George: You have a positive here and then it [the test charge] wants to go here and here, and it doesn't know where to go.
>
> Michael: Yeah, you're correct.

At this point, George and Michael begin writing, indicating that they find their solutions sufficient, and Lindsay begins reading the next problem on the worksheet.

In this exchange, the students determined that they all had solutions that they individually found sufficient. They further assessed whether their solutions align. In this way, they engaged in a group negotiation of their responses.

4.4.4 Disruption and repetition of the individual AMEGs

The data presented in the previous section describes the students' second, and successful, attempt at a group negotiation of their responses. The group negotiation of their responses is not trivial, however, and so a disruption caused students to struggle with this negotiation on their first attempt. The data presented in this section will regard the students' first attempt at a group negotiation of their responses (thick solid line in Figure 4.1) and their following moves. The disruption was a series of statements made by a student that caused all group members participating in the SAMEG to become dissatisfied with the individual solutions they had arrived at following their individual AMEGs. When the disruption occurred, students sought to again find solutions they personally found sufficient, and did so by returning to their individual AMEGs (thin dashed lines in Figure 4.1).

The students (with the exception of Buster who still was not engaged) were observed to move through the original AMEG a first time individually and arrive at solutions they personally found sufficient, seen in all three students quietly writing on their worksheets. After a few seconds of this silence, however, Michael stops writing (00:52-00:57),

> Michael: Oh actually, will a charge remain where we placed it if it's... oh yeah but...

At this point, George and Lindsay stop writing, and begin watching Michael. The three students now return individually to the original AMEG path they had played before. For example, after his speech and discontinuing his writing, Michael, who played RA path in his first pass, reasons conceptually for the duration of (02:06-05:08), saying things like (03:56-04:06),

> Michael: So it's [a charge] pushing away from it [the test charge]. . . and this negative is going to be attracting it [the test charge], so it's going to get pushed in that direction.

before proposing another answer at (05:08), suggesting that he again followed the RA path. Similarly, Lindsay and George were observed to follow the AJ path as they had on their first individual passes through the original AMEG.

By this series of events, we can interpret that Lindsay, Michael, and George became dissatisfied with their individual solutions as a result of Michael's comment, then returned to their individual AMEGs. The presence of both the RA and AJ paths suggests that this is in fact a repeated playing of the original AMEG on an individual basis. Additionally, the three students did not find their new solutions sufficient simultaneously, as determined by being observed to write quietly. Lindsay found her solution sufficient first at (04:16), followed by Michael at (05:08), followed by George at (05:22). This further suggests that they were playing the original AMEG individually following the disruption.

4.4.5 Exit condition

The exit condition for the SAMEG is, like the AMEG, a sufficient solution [29]. Due to the group context of the SAMEG, this manifested as all students having solutions that they individually found sufficient. The group context of the SAMEG further adds the necessity of the group negotiation of their responses. As described previously, there was a point at which all three students found their solutions sufficient, but did not exit the SAMEG due to the disruption caused by Michael. Instead, the group only began working on the next problem, evidenced by Lindsay reading it aloud for the group, after they had completed the group negotiation of their responses successfully. Thus, in order for the students to exit the SAMEG, it was necessary for them to all have sufficient solutions and also to have successfully completed the group negotiation of their responses.

4.4.6 Ontology

In the previous sections, we discussed the structure of the SAMEG. The ontology of the SAMEG is described by its knowledge base and its epistemic form [28]. The knowledge base of the SAMEG is the set of physics resources that the students activated as they worked on the problem. The epistemic form of the SAMEG is a group negotiated worksheet response. The students' actions throughout the SAMEG were directed by the need to complete the worksheet that they had been assigned together. This negotiated worksheet response provided external structure that guided the students as they played the SAMEG [27, 28].

4.5 Discussion and conclusions

The context of this study undoubtedly played a role in the identification of the SAMEG. Due to the collaborative nature of the environment, the students needed to navigate their different and possibly opposing problem-solving strategies in order to successfully complete the assignment, and what we observed was the emergence of a shared epistemic game, comprised of both individual and group moves.

The particular students analyzed in this case may have had an impact on the appearance of the SAMEG. In this group, Michael disrupted the first attempt at a group negotiation of their responses. It is possible that another group may not face such a disruption, and therefore not repeat their individual AMEGs. The particular students may have also impacted the appearance of the SAMEG via Buster's low level of engagement. The group of four students functioned largely as a group of three. It is unclear what impact this may have had on the actions of the three participating students and how the SAMEG then manifested.

As epistemic frames and games are related, it is worth noting that the SAMEG appears to occur within the "discussion frame" [30]. Throughout the episode, the students spoke in clear voices towards each other, maintained eye contact, and responded to each other's comments, indicating that they all worked under the assumption that their attention should be on one another. The discussion frame is broad, however, and does not attend to group members' individual frames [125]. The SAMEG can allow for a description of individuals' different frames within a shared, group-level discussion frame. Namely, it can be inferred that students engaging in the RA path while participating in the SAMEG are not framing the activity in quite the same way that students engaging in the AJ path are. While it is not entirely clear what causes these alternative frames, the SAMEG nonetheless provides a lens wherein individual students' frames may be differentiated within a group-level discussion frame, and such a lens can be productive in the analysis of the complexities of student reasoning in collaborative learning environments.

Chapter 5

Development of a modes of collaboration framework

The following chapter was published in Physical Review Physics Education Research [57], and is presented here with minor modifications from its appearance in publication. It was published with second and third authors Paul W. Irving and Marcos D. Caballero.

5.1 Abstract

Group work is becoming increasingly common in introductory physics classrooms. Understanding how students engage in these group learning environments is important for designing and facilitating productive learning opportunities for students. We conducted a study in which we collected video of groups of students working on conceptual electricity and magnetism problems in an introductory physics course. In this setting, students needed to negotiate a common understanding and coordinate group decisions in order to complete the activity successfully. We observed students interacting in several distinct ways while solving these problems. Analysis of these observations focused on identifying the different ways students interacted and articulating what defines and distinguishes them, resulting in the development of the Modes of Collaboration framework. The Modes of Collaboration framework defines student interactions along three dimensions: social, discursive, and disciplinary

content. This multi-dimensional approach offers a unique lens through which to consider group work and provides a flexibility that could allow the framework to be adapted for a variety of contexts. We present the framework and several examples of its application here.

5.2 Introduction

Interactive instruction is becoming increasingly common in introductory physics classes, with more instructors implementing techniques such as small group discussions, group problem solving, and team-based projects. These techniques have been found to be more effective by some metrics [19, 21, 25, 48, 51], but a number of aspects remain ill understood [47, 52]. Much work remains to be completed to better understand these interactive learning environments and the effects they have on student learning [126, 127, 130].

Several lenses aimed at understanding various aspects of how students engage in such work have been developed. Some seek to assess the impact of collaborative work on individual student learning [19, 47, 48, 112]. Others attempt to understand the different ways students may perceive group work [30, 120, 121, 125]. Still others aim to identify ways to optimize group work [31, 129, 133]. Another broad area of investigation has endeavored to categorize the ways that students engage with group work. Such work has approached this goal in a variety of ways, including a particular focus on social aspects of group work [21, 119, 132], discursive aspects of group work [118, 128, 129, 173], and framing aspects of group work [15, 112, 124, 130]. In this paper, we present a new framework called the Modes of Collaboration that attends to three dimensions: social, discursive, and disciplinary content. We did not make use of framing as a dimension directly, as we found that considering the ways in which students discussed physics content was better able to capture our observations, however, this dimension does have a relationship to framing (see Framework section).

By attending to all three of these dimensions simultaneously and independently, the Modes of Collaboration is a framework that is simple to apply, but that still provides multifaceted insight into students' engagement with group work. In addition to presenting the framework here, we identify four specific Modes that students engaged in within our context based on observation of a small set of video data from one day of class work. The Modes of Collaboration framework presented here acts as a proof that student group work can be described along the three dimensions, and we propose that it is flexible enough to be used in other contexts beyond the one analyzed here.

5.3 Background

Group work has long been an area of investigation in physics education and education more generally, and has been studied from many different perspectives. Some work focuses on individual content understanding, typically using pre and post measures of individual learning to measure the impact of group work [19, 47, 48, 112]. Other studies have attended to student perceptions of group work, usually through the observation of student behavior in groups or through interviews with students, aiming to more qualitatively understand students' experiences [30, 120, 121, 125]. Research has also been conducted on ways that group work might be optimized to achieve the best outcomes for students, for example, considering which types of activities or which group compositions result in the greatest learning gains for students [31, 129, 133]. Finally, a great deal of work has been done with the aim of developing ways to categorize student engagement with group work. This has been done in a variety of ways, including attending primarily to social dynamics [21, 119, 132], student discourse [118, 128, 129, 173], or student perceptions and framing [112, 130]. Below, we offer additional background on the work conducted along each of these lines to frame and situate the Modes of Collaboration framework. While much of this previous work is not specific to undergraduate students or to physics, it is nonetheless valuable in informing and providing context for our work. Elementary school students and college students are of course different in many ways, and even college math students and college physics students are different, but themes found in one of these populations can still be productive when considering the other. We describe some of these themes below, and demonstrate their utility in our context in the Framework and Modes of Collaboration sections.

5.3.1 Individual content understanding

Much early research surrounding group work focused on identifying or assessing the impact of collaborative work on individual students' understanding of the content. In a study of high school science students, Amigues compared the individual post-test performance of students who worked on a preceding activity alone to students who worked on the preceding activity in dyads, and found that the students who worked in dyads were more successful on the post-test [112]. In a later study specific to college physics students, Heller et al. tracked how students' individual problem solving abilities developed over the duration of a semester-long course that implemented collaborative group problem solving sessions, and found that their individual problem solving abilities improved [25].

In efforts to similarly study the impact that group work has on individual student outcomes, many studies have made use of concept inventories as a metric. These concept inventories [16–18] are multiple-choice exams centered on a particular content area, which students complete individually. While they are unable to capture many aspects of a student's experience, they have historically been used as an indicator of a student's understanding of the concepts probed. Lumpe et al. used the Photosynthesis Concept Test (PCT) to compare the learning outcomes of high school students who completed a task on photosynthesis individually to students who completed the same task in a group. They found that students who had worked in groups were more successful on the PCT, but that not every member of a given group experienced the same degree of improvement [21].

Studies such as these have been important in providing evidence of group work's efficacy, albeit as measured by metrics that have limitations [49, 115, 116]. What they cannot provide, however, is an understanding of what happens during group work. By focusing on comparisons between students' pre- and post- instruction understanding, they neglect to consider the ways in which students interact and speak while engaging in group work; the social and discursive dimensions. Furthermore, a strict focus on individual content understanding does not account for the aspects of learning that may occur beyond purely cognitive models [174].

5.3.2 Student perceptions

In addition to identifying the ways in which group work impacts individual student content understanding, efforts have been made to examine how students perceive group work. In a study of elementary students working on a science task in groups, Anderson et al. conducted observations and interviews to understand students' goals and feelings of success or lack thereof during the activity [120]. They defined three areas on which students may focus their attention when working in groups: task structure and accountability systems, interpersonal relationships, and scientific activity. Based on Anderson et al.'s observations and interviews with students after the activity, they found that the students focused primarily on interpersonal relationships and task structure goals, and that students did not appear to focus as much on the scientific activity component. Additionally, Anderson et al. found that students felt that they were successful at the activity overall. Grindstaff et al. also examined students' perceptions of collaborative work by interviewing students working on short-term research projects with peers [121]. They found that students discussed several types of support that peers may provide when working collaboratively: emotional, technical, and cognitive, and that there was a great variance in which ones students reported as being most relevant or important.

Student perceptions of group work have also been examined through the construct of epistemological framing [15, 30, 123–125]. Scherr et al. developed this construct by building upon previous work on framing in general, which they characterized as "how an individual or group forms a sense of 'What is it that's going on here?'" From this, they narrowed to examining how students frame activities specifically related to knowledge, and called this epistemological framing [30]. In analyzing the discussion of undergraduate physics students working on tutorials, they observed four behavioral clusters that they then mapped to different epistemological framings. These frames were: discussion, worksheet, TA, and joking. In another study of students working collaboratively, Irving et al. proposed an alternative way to understand students' epistemological framing [125]. In their work, they define two axes with which to characterize students' framing, rather than the discrete categories presented by Scherr et al. One axis describes the degree to which a student's statements are serious or silly, and the other describes the degree to which a student's discussion is narrow versus expansive.

This type of work on students' perceptions of the tasks and goals in group work and their perceptions of group work itself provides a complementary perspective to the insights gained by studies of individual student content understanding. While the latter attends to outcomes, the former attends to the process and experiences of students. Studies of student perceptions of group work frequently focus on social aspects, sometimes discuss discursive aspects, and less frequently consider disciplinary content-related aspects of group work, but rarely attend to all three simultaneously.

5.3.3 Optimizing group work

There have also been efforts made to identify the ways to best design and implement group work to maximize its benefit to students. Heller et al. examined the effect that group makeup had on the success of groups [31]. Their results indicated that heterogeneity with respect to incoming ability produced the highest rate of success for groups. They also found that groups that were homogenous with respect to gender, or groups in which there were more women than men were most successful. In addition to examining group makeup, they investigated the impact of giving students explicit guidance on how to work in groups. Students were given one of three roles: manager, skeptic, and checker/recorder. They found that assigning these roles reduced issues of individuals becoming too dominant in groups, or groups being conflict-avoidant. They also found that giving students time to engage in explicit discussion of their group's interactions was beneficial. Van Boxtel et al. examined the impact that having students complete individual preparatory work before working in groups had on their success in those groups [129]. Their results indicated that the individual preparatory work led to students asking each other more questions while working together, and improved individual learning gains measured after the group work. Webb et al. sought to identify the conditions that must be met in order for students working in peer-directed groups to give and receive help in a productive way [133]. They propose that in order for received help to be effective it must be relevant, timely, correct, and sufficiently elaborated. They also identify three more conditions necessary for received help to be effective: the recipient must understand the help, the recipient must have a chance to make use of the help, and the recipient must act on that chance to use the help. The authors go on to use these conditions to identify the responsibilities of the help-seeker, help-giver, and teacher in making these conditions possible.

Studies seeking to optimize group work are essential to providing students with the best learning experiences in collaborative environments. Their results can directly inform instructional choices. Similar to the studies on individual content understanding, however, they frequently compare students' pre- and post- performance, and do not attend to the processes that occur during group work. In doing so, they typically do not attend to the discursive and social dimensions of group work.

5.3.4 Categorizing student engagement with group work

Another area of investigation has endeavored to categorize the various ways that students engage with group work. Some of this work has focused primarily on the social dimension when developing categories. In the work by Lumpe et al. previously discussed, they identified two general interaction styles that students may experience when collaborating: consonant, or generally agreeable, and dissonant, or generally negative [21]. Roth et al. also attended to social factors, and categorized the ways in which students may navigate a disagreement, observing that they would proceed in several distinct ways: collaborative construction, adversarial exchanges, and the formation of temporary alliances [132]. Richmond et al. identified the different social roles that students took on when working in groups. They observed four social roles: leader, helper, active non-contributor, and passive non-contributor [119]. They further found that students taking on a leadership role would lead in one of three styles: inclusive, persuasive, or alienating.

Others seeking to categorize students' engagement in group work have done so by attending to the discursive dimension. Hogan et al. examined the ways that students speak to one another when working in peer guided group discussions and teacher guided group discussions [128]. They identified four modes of discussion: peer knowledge construction, teacher guided knowledge construction, logistical conversation, and off task conversation. They found that the relative occurrence of these modes varied greatly across groups. One hypothesis they offered for this result was the teacher spending more or less time with a group depending on their level of prior knowledge. In the Van Boxtel work described earlier, the authors identified several styles of student interactions based on their discourse: question, conflict, and reasoning [129]. They found that questioning episodes occurred most frequently, and that reasoning episodes were most likely to lead to elaboration of ideas. Haussman et al. also made use a categorization scheme attending to discourse [118]. They analyzed three proposed mechanisms of collaborative learning: other directed explaining, self directed explaining, and co-construction. The authors found that co-construction led to high individual learning gains for both participants as measured by an individual post test, and self directed and other directed explaining led to higher individual learning gains for the students giving the explanations. Other directed explaining was more effective for the listener than self directed explaining was for the listener.

Students' engagement with group work has also been categorized by attending to their perceptions of collaboration and the activity on which they are working. As described earlier, both the work of Scherr et al. and Irving et al. set forward frameworks with which to classify students' behavior in groups based on their epistemological framing [30, 125].

All of these methods of categorization provide valuable frameworks to understand students' engagement with group work. Applying such categories can offer a way to make sense of what students find important, how they perceive each other, and how they speak to one another. As outlined though, these frameworks typically attend to only one dimension of group work. A framework that categorizes students' engagement with group work while simultaneously attending to discursive, social, and disciplinary content dimensions can provide insights that focusing on only one may be unable to provide. The Modes of Collaboration framework attempts to do just this, outlining several distinct Modes of student interaction that are characterized by their discourse, their social interactions, and their engagement with the disciplinary content.

5.4 Study context

The data presented in this paper were collected from an introductory electricity and magnetism course at a large university. There were approximately 120 students in the course, and most were sophomore life-science majors. The students all attended lecture three times a week, and a laboratory session once a week in sections of approximately 20 students. In these laboratory sessions, students worked collaboratively in groups of three or four on a variety of activities depending on the week (traditional labs, tutorials, conceptual and calculational problems, etc.). For this study, nine unique groups of students were video recorded as they worked during their weekly laboratory sections, resulting in a total of 2 hours and 29 minutes of video.

The activity they are working on is a series of three conceptual questions about the electric field and electric potential energy in the area around different distributions of charge. Students would first read the problem statement without knowledge of the charge distribution in question. They would then select as a group a representation of the charge distribution (electric field lines, electric field vectors, or electric potential lines) to view, based on what they thought would be most helpful in answering the problem. An instructor would then bring them their requested representation, and the students would use it in order to answer the problem. Each question had a well-defined correct answer, but could be solved using multiple methods. For example, one might use the representation to deduce where the source charges are located, then use this information to answer the question, or one might use the representation directly to answer the question, without considering the location of the source charges. This activity was similar to those they had experienced in previous laboratory sessions in that it required cooperative group work on conceptual problems, but was unique in that it required a level of explicit planning and strategy (in the selection of a representation) that was not typically necessary.

5.5 Methods

Analysis began with multiple coarse viewings of the video data, attending to instances of explicit interaction among students where their discussion related to the activity. An explicit interaction is one that involves two or more students speaking, and an interaction that is related to the activity is one wherein the content of the students' speech was related to the physics content present in the activity. Focusing on these segments reduced our data to 1 hour and 11 minutes of video. Once these segments were identified, they were viewed successively, seeking emergent trends in the student interactions and behavior observed. In these emergent trends, distinct patterns were found that related to the three dimensions: social, discursive, and disciplinary content. The data was then split into "episodes", which were defined by a shift in a group's behavior along any of the three dimensions. For example, in a given segment of video, if a group's interaction with the disciplinary content appeared to change, this would be considered the end of one episode, and the beginning of a new episode. For each episode, the students' interactions were characterized along each dimension independently, and then episodes having all three dimensions in common were grouped and termed Modes. Preliminary definitions for each Mode were crafted based on exemplars, then refined through multiple viewings of every illustrative episode.

Similar to the work of Hogan et al., our procedure of analysis was not predetermined, instead emerging from our observations, and quantitative inter-rater reliability in the identification of Modes or dimensions was not our goal [128]. Our goal was to craft definitions for the Modes emerging from this data set that qualitatively described the speech and behavior seen in each Mode. The first author's knowledge of the data made her best suited to making such identification and analysis decisions, and the co-authors provided critical feedback on these decisions throughout the development of the framework. Through iterating on this process, we arrived at robust Mode definitions that were able to capture the commonalities seen in each instance of each Mode, and also accounted for the differences seen among Modes.

5.6 The Framework

The Modes of Collaboration are defined along three dimensions: social, discursive, and disciplinary content. Each individual Mode is characterized in a particular way within each of these dimensions.

5.6.1 Social dimension

The social dimension addresses the overall tenor of the students' interactions with one another. It accounts for the atmosphere in which the students' conversation takes place. To describe the social dimension, we make use of the interaction styles identified by Lumpe and Staver [21]. In their work, they observed that groups of students would interact in ways that were consonant or dissonant. Consonant interactions were characterized by agreement among students and the validation of peers' ideas, while dissonant interactions were characterized by conflict (taken here to mean explicit disagreement), a lack of recognition, or criticism of peers' ideas. It is important to note that consonant interactions are not necessarily better than dissonant interactions. For example, respectful critiques of one another's reasoning can lead students to a more robust understanding. Furthermore, in selecting this scheme of categorization for the social dimension, we do not claim that it fully describes the richness of students' social interactions. Rather, the assessment of consonant versus dissonant provides a simple and productive way to determine the general tone of a group's discussion, which is what we define the social dimension of the Modes of Collaboration framework to be.

5.6.2 Discursive dimension

The discursive dimension deals with the way in which students communicate with each other. It describes the ways that students present their ideas and the structure of their conversation. The discursive dimension is grounded in Hogan's work on knowledge construction and Toulmin's work on argumentation [128, 175]. In their work, Hogan et al. identified three modes that described the interactions of their students: knowledge construction (peer or teacher-guided), logistical, and off task. Knowledge construction refers to when the conversation is related to scientific phenomena, logistical refers to when students discuss tasks necessary to complete the activity but not related to scientific content, and off task refers to when students discuss things unrelated to the task entirely. Since we sought to develop a framework that describes students' interactions when they are discussing physics, the Modes of Collaboration all occur within the knowledge construction mode identified by Hogan et al. We therefore could not use their three modes as a scheme with which to further analyze the student interactions we were interested in, but we did make use of an element of their analysis. In developing their three modes, Hogan et al. identified three interaction patterns. These interaction patterns were consensual, responsive, and elaborative.

Consensual interactions are those in which only one student makes substantive contributions, while other students simply agree, accept (explicitly or passively), or repeat the contributions of that student. Responsive interactions are those in which multiple students make substantive statements. Elaborative interactions are those in which multiple students make substantive statements, and those statements build off preceding statements by making connections between ideas, correcting someone's idea, or disagreeing with someone's idea and providing a counterargument. In addition to Hogan et al.'s interaction patterns, we used argumentation as a way to characterize student discourse. As conceptualized by Toulmin, argumentation is composed of evidence, a claim made based on that evidence, and warrants justifying how the evidence supports the claim. If students were observed to make use of these elements when presenting their ideas, their discourse was characterized as argumentation. It is worth noting that argumentation falls under the elaborative interaction pattern described by Hogan et al. Nonetheless, the choice to supplement Hogan et al.'s interaction patterns with Toulmin's argumentation was made because separating discourse that had formal argumentation from that which had a "non-argumentative" elaborative interaction pattern was productive. The distinction allows the Modes of Collaboration framework to attend to the difference between a series of unsubstantiated ideas shared by students, and a sequence of explicitly supported claims. These two interactions may suggest different motives for the students and may have different results for their further interactions, and we therefore wanted to capture this difference in the discursive dimension.

5.6.3 Disciplinary content dimension

The disciplinary content dimension addresses the ways that the students discuss physics. It describes the types of physics content on which their conversations focus. In the previously mentioned work by Irving et al. on epistemological framing, they identified an axis that described the scope of students' framing, with narrow at one end and expansive at the other end [125]. We do not make direct use of this construct, as our work does not attempt to identify the ways in which students frame the activity. Instead, we define students' discussion to be related to specific physics content or abstract physics content. These terms were selected in order to convey the degree to which the content being referenced is tied concretely to the situation the students are analyzing. When students discuss specific physics content, they focus on physics content applied specifically to the question at hand, such as discussing the orientation of the electric field vectors in the diagram presented in the question. Abstract physics content discussion refers to discussion that is not directly related to producing an answer to the activity question. Instead, it centers on concepts in general, such as a discussion of the meaning of electric potential energy. Thus, based on the scope of the physics content that the students discussed, the disciplinary content of their discussion was characterized as either abstract or specific.

A Mode is defined by its classifications in each of the three dimensions. It is worth noting

Dimension	Categorizations
Social	Consonant Dissonant
Discursive	Consensual Responsive Elaborative Argumentation
Disciplinary content	Specific Abstract

Table 5.1: The three dimensions and the categorizations possible within each dimension

that the dimensions are treated independently. Each dimension is assessed solely based on the discourse and behaviors observed, without reference to categorizations made along the other dimensions. It could be that some combinations do not occur (consonant social dimension and argumentation discursive dimension appear contradictory, for example), but by coding across each dimension individually, we do not make any assumptions about such connections. It is also important to recognize the grain size that the Modes of Collaboration framework considers. When applying the framework, data is broken into episodes defined by apparent shifts in a group's interaction along any of the three dimensions. It is these demarcated episodes that are then analyzed along the three dimensions. A summary of the dimensions and the categorizations possible within each appears in Table 5.1.

5.7 The Modes of Collaboration

In this study, we identified four distinct ways in which students interacted: Debate, Informing, Co-construction of an Answer, and Building Understanding Towards an Answer, which are described below in detail. Table 5.2 provides an overview. The following subsections each begin with a description of how the Mode manifests based on student behavior, then outlines how it is defined using the three dimensions.

Mode	Social dimension	Discursive dimension	Disciplinary content dimension
Debate	Dissonant	Argumentation	Specific or abstract
Informing	Consonant	Consensual	Specific
Co-construction of an Answer	Consonant	Elaborative	Specific
Building Understanding towards an Answer	Consonant	Elaborative	Abstract

Table 5.2: The Modes of Collaboration identified in this data and their characterizations along each of the three dimensions

5.7.1 Debate

In the Debate Mode, two students engage in a dialogue, arguing their conflicting understandings of the concepts or responses to the activity prompts, while the remaining students in the group do not speak. It will continue until one student ultimately capitulates and accepts the other's reasoning, or at least ceases to argue their own. The Debate Mode is characterized by dissonant interactions in the social dimension, argumentation in the discursive dimension, and can be characterized by specific or abstract content in the disciplinary content dimension. The two episodes presented here happen in immediate succession, and demonstrate an example of specific Debate and an example of abstract Debate. In the episodes, Lindsay and Michael work on a problem that asks them to determine if there are any points of equilibrium in the area surrounding an electric quadrupole using an image of the electric field vectors. Immediately before the transcript begins, Lindsay has argued that the electric field vectors cancel.

5.7.1.1 Episode A1

Michael: Yeah, they're [electric field vectors] not in opposite directions. They all are going in the same direction, so they're not cancelling.

Lindsay: Well no no no, they are. These are, [gesturing at the electric field vectors on the image because this one's going this way, and this one's going this way. And then these two are going in opposite directions, as well. So, they are in opposite directions.

5.7.1.2 Episode A2

Michael: Well, you remember the tutorial homework we did? And it had equal magnitude charges, but one was negative and one was positive, and they added together.

Lindsay: Yeah... [no longer pointing at the image]

Michael: Ones that are of the same sign and equal magnitudes cancel out.

Lindsay: Why would they cancel if they're the same sign, when you add them together?

5.7.1.3 Social dimension

When engaged in the Debate Mode, the two active students interact in a dissonant way. For the duration of the Mode, the two Debating students explicitly disagree with one another. Rather than validating each others' ideas, they put forth criticism. In the examples, there are multiple instances of explicit disagreement. In lines 1-2, Michael's first response to Lindsay's argument that the field vectors cancel, he directly disputes her claim. Following this, in lines 3-6, Lindsay reiterates her belief, contradicting Michael's ideas. In addition to this overt conflict, Lindsay and Michael explicitly critique each other's ideas. In lines 1-2, Michael not only disagrees with Lindsay, but also explains the flaw he finds in her ideas. Similarly, in lines 3-6, Lindsay explains why she believes Michael is incorrect. Finally, in lines 12-13, Lindsay pushes back against a perceived weakness in Michael's reasoning. These critiques, along with the conflict present in these episodes, indicate that they both take place with a dissonant interaction style.

5.7.1.4 Discursive dimension

Along the discursive dimension, the Debate Mode is characterized by argumentation. The two Debating students making use of evidence, claims, and warrants as they present their ideas to one another. In the examples, we see Michael and Lindsay make use of these elements of argumentation in their discussion. In lines 1-2, Michael presents both his evidence, the electric field vectors are pointing in the same direction, and his claim, that they do not cancel. Later, in lines 7-9, he provides his warrant. He refers to a previous assignment to provide further information on why vectors going in the same direction do not indicate cancelling. In lines 3-6, Lindsay presents her competing claim, that the vectors do cancel, and evidence, that the image shows the vectors pointing in opposite directions. Such implementation of claims, evidence, and warrants indicates that the students are engaging in argumentation in these episodes.

5.7.1.5 Disciplinary content dimension

The Debate Mode may be specific or abstract in the disciplinary content dimension. Students may discuss physics content directly related to the question at hand, or they may focus their conversation on general cases and abstract concepts. In the examples, we see both kinds of disciplinary content present. In lines 1-6, Michael and Lindsay both attempt to directly answer the question. Each refers to the vectors on the image representing the charge distribution the question requires them to consider. Thus they consider specific physics content. In lines 7-13, the focus of their discussion shifts. Michael no longer refers to the question in the activity. He expands the conversation to discuss charges and “cancelling” more generally. In this way, the conversation now focuses on abstract physics content, indicating the beginning of a new episode. The students’ behavior has not shifted along the social or discursive dimensions, however, and so Episode A2 is still Debate, but now a Debate of abstract content.

5.7.2 Informing

In the Informing Mode, one student, the “Informer”, explains his or her ideas about the question at hand to one or more other group members. The Informer consistently offers his or her thoughts while other students do not; instead they only listen to or ask questions of the Informer. This continues until all participating group members begin writing the results of the discussion on their worksheets. The Informing mode is characterized by consonant interactions in the social dimension, consensual interaction patterns in the discursive dimension, and specific content in the disciplinary content dimension. In the example presented here, Jim, Erin, and Angela engage in the Informing Mode, with Erin acting as the Informer, as they attempt to determine how to maximize electric potential energy when placing a test charge near a given charge distribution, using a diagram of the equipotential lines surrounding the distribution.

5.7.2.1 Episode B

Erin: So all those rings [pointing at equipotential lines] show the same potential energy – one right. So the one that is the smallest ring has the most potential energy.

Angela: Ohh.

Jim: Okay, so we just put it [the test charge] right in the middle? [looking at Erin]

Erin: On the smallest ring.

Jim: On the smallest ring.

Angela: On the smallest ring.

Erin: Yeah.

[All three begin quietly writing on their worksheets.]

5.7.2.2 Social dimension

In the Informing Mode, students interact in a consonant way. There is no explicit conflict among group members or criticism of peers' ideas. Instead, the ideas presented are recognized and validated without resistance. In the example, Erin presents her thoughts about the answer to the question in lines 1-3. After this statement, the conversation contains implicit validation of Erin's statement by Angela in line 4, and explicit validation of Erin's idea by both Jim and Angela in lines 8 and 9, respectively. There is no criticism or rejection of Erin's ideas at any point, and no other students present ideas that could be subject to criticism or rejection. Thus we see that this episode is characterized by a consonant interaction style.

5.7.2.3 Discursive dimension

During the Informing Mode, students' discourse is characterized by consensual interactions. The Informer is the only student who makes substantive contributions to the conversation, while the other students either explicitly agree and accept the Informer's statements, or ask short clarifying questions. In the example, Erin is the only student who makes a substantive contribution with her statements about the equipotential lines in the diagram in lines 1-3. In contrast, Angela responds with an implicit acceptance of Erin's statement in line 4, and in line 9, a direct repetition of a statement made by Erin. Jim's contributions consist of a question in lines 5-6 clarifying Erin's initial statement, and in line 8, a direct repetition of Erin's statement. In this way, we see that this episode has a consensual interaction pattern, with Erin acting as the substantive contributor.

5.7.2.4 Disciplinary content dimension

In the Informing Mode, the disciplinary content of the students' conversation is characterized by specific content. The students discuss physics content as it relates directly to producing an answer to the question at hand. They do not discuss physics concepts in the abstract or expand their conversation to general cases. In lines 1-3 of the example, Erin presents an answer to the question the group is discussing. She does not discuss the meaning of electric potential energy or the function of equipotential lines in general. The only other statement in the episode that is not a simple assent or repetition is Jim's question in lines 5-6. With this question, he confirms the answer that Erin is proposing, still limiting the scope of the physics content being discussed to the question at hand, and not abstract concepts. Accordingly, we see that the conversation in this interaction centers on specific content.

5.7.3 Co-construction of an Answer

In the Co-construction of an Answer Mode, two or more students work towards creating an answer to the question on which they are working. As the students work towards this answer, nearly every contributed statement is acknowledged and built upon. A student is considered to be participating in the Co-construction of an Answer if he or she makes statements relevant to the conversation during the episode. Non-participating students may or may not appear to be paying attention, but are not considered a part of the Co-construction of an Answer regardless, as they are not aiding in the construction of the answer. The Co-construction of an Answer Mode is characterized by a consonant interaction style in the social dimension, elaborative interaction patterns in the discursive dimension, and specific physics content in the disciplinary content dimension. In the example here, all four students in the group engage in the Co-construction of an Answer Mode as they consider which way a test charge would move when placed near an electric dipole using an image of electric field vectors.

5.7.3.1 Episode C

Lindsay: So, if we put a negative charge here at this X, it's asking you which way it would move after it's released.

Michael: It would move towards the outside middle.

Lindsay: What do you mean by outside middle? [looking at Michael]

Michael: Well, it's moving… [gestures hand over the image, then pulls back, hesitating]

Lindsay: [looking at Michael, then speaking] This [the image] is the electric field at each point…

George: Wouldn't this be, this [gesturing at a field vector] is showing where a positive test charge would go, so wouldn't the electric charge move opposite?

Lindsay: Well it's a negative, so wouldn't it just move… [takes the image and starts to draw on it]

Oscar: This is negative though, right here [indicating a point on the image], isn't it?

Lindsay: Oh, it is negative; you're right, ok [erases what she's drawn] so it would move… opposite.

5.7.3.2 Social dimension

The Co-construction of an Answer Mode is characterized by consonant interactions in the social dimension. There is no explicit conflict in the group's discussion, and the ideas that group members put forth are acknowledged and validated. In the example, nearly every statement made is acknowledged by the following statement. For example, Michael proposes an answer in line 3, and in her clarifying question in line 4, Lindsay makes direct reference to Michael's statement. In lines 7-8, while Lindsay does not explicitly acknowledge Michael's attempt to answer her clarifying question, the fact that she waits for Michael to trail off, then begins her statement by looking at him indicates that she is attempting to aid him in his hesitation. In the episode, we also see the explicit validation of peer ideas. In line 15, Lindsay specifically says, "you're right" in response to the idea that Oscar has presented in lines 13-14. Beyond the recognition and validation of peer ideas, there is also no explicit conflict present in the group's discussion. At no point do any of the students outright disagree with something another student has said. The closest statement to a disagreement in the episode comes from Oscar in lines 13-14, where he points out to Lindsay that a point charge she had been considering positive is in fact negative. Even in this statement, however, Oscar does not present his correction as a disagreement. Instead, he simply offers a new idea, phrasing it as a question, and not a rejection of Lindsay's understanding. This lack of explicit conflict, and the recognition and validation of peers' ideas indicate that the interactions in this episode are consonant.

5.7.3.3 Discursive dimension

The discursive dimension of the Co-construction of an Answer Mode is characterized by elaborative interaction patterns. All participating students not only make substantive contributions to the discussion, but also explicitly connect those contributions to those of the other students. In the example, all four students in the group provide statements that are relevant to their discussion of the question and also explicitly relate their statements to each other's. In lines 7-8, Lindsay provides her understanding of what the image is showing them, thus offering a substantive contribution to the conversation. In lines 9-10, George responds by building off of this, offering a more specific understanding of what the electric field vectors show. With this response, he contributes substantively to the conversation, and also explicitly connects his ideas to what Lindsay has contributed. Earlier in the conversation, Michael provides a substantive contribution in line 3 when he proposes an answer to the question, and in lines 5-6, provides another substantive contribution that is directly connected to the question Lindsay asks him in line 4. In lines 13-14, Oscar also contributes a substantive and explicitly connected statement when he offers his correction of Lindsay's thoughts in lines 11-12 . These substantive contributions and the explicit connections that the students make among them are what show this to be an elaborative interaction pattern.

5.7.3.4 Disciplinary content dimension

The disciplinary content dimension of the Co-construction of an Answer Mode is described by specific physics content. The students focus their conversation on physics as it relates directly to the question they are working on, and do not attempt to expand their conversation to general cases or abstract concepts. In the example, the whole of the discussion is centered on producing an answer to the question, "which way will the charge move?". In line 3, Michael provides a possible answer. In lines 7-10, Lindsay and George discuss the image of the charge distribution that the question asks them to consider, with Lindsay describing what the image shows, and George describing what the individual vectors on the image show. In neither case do they make claims about what electric fields or field vectors show in general, instead they refer specifically to the image they have. In lines 7-10, Lindsay and George both use the image to propose answers to the question. In response to Lindsay's answer, Oscar brings the group's attention to an element of the image in lines 13-14. Finally, Lindsay incorporates this and presents an answer again in lines 15-16. Throughout this episode, the students' conversation is focused on producing an answer to the question using information from the image they have been provided. This attention to the question and the absence of discussion of the meaning of physics concepts in the abstract indicate that this conversation is characterized by specific physics content.

5.7.4 Building Understanding towards an Answer

In the Building Understanding towards an Answer Mode, two or more students discuss physics concepts in a way that is not directly related to answering a component of the activity, instead seeking to develop an understanding of the underlying concepts. Due to the nature of the activity the students in our data completed, this understanding was ultimately be aimed at answering a question in the activity, but nonetheless, the Building Understanding towards an Answer Mode focuses first on developing an understanding. Similar to Co-construction of an Answer, during Building Understanding towards an Answer, nearly every statement contributed is recognized and built upon. Also as in the case of Co-construction of an Answer, a student is only considered to be participating in the Building Understanding towards an Answer Mode if they verbally contribute to the discussion, as they otherwise are not contributing to the building of the group's understanding. The Building Understanding towards an Answer Mode is characterized by consonant interactions along the social dimension, elaborative interaction patterns along the discursive dimension, and abstract physics content along the disciplinary content dimension. In the example here, Leslie, Ben, and Ron engage in the Building Understanding towards an Answer Mode as they discuss the meaning of electric potential energy and its relationship to electric field lines while they work on a question asking them to determine how to maximize electric potential energy when placing a test charge near a given charge distribution, using a diagram of the electric field lines surrounding the distribution.

5.7.4.1 Episode D

Leslie: What does it mean though to have electric potential energy?

Ben: Remember here we did that question? [flipping to a previous page in the activity] It was a question where you compared the electric potential energy between like A and B, and the answer was A, here, has the greater electric potential energy. So I think it's how close you are to the actual…

Ron: [looking at Leslie] In other words, how much energy you need to put in to like move it.

5.7.4.2 Social dimension

The social dimension of the Building Understanding towards an Answer Mode is described by consonant interactions. The participating students recognize and validate one another's ideas, and there is no explicit conflict present in the discussion. In the example, Leslie begins the conversation by asking the group a question in line 1. Ben acknowledges Leslie's question and engages with it when he answers her in lines 2-5. After this, in lines 6-7, Ron acknowledges both Leslie's question and Ben's answer by providing another answer to Leslie's question, and by framing it as "in other words" to Ben's answer. In addition to this consistent recognition of each other's statements, the episode also demonstrates a lack of conflict. In lines 2-7, neither Ben nor Ron disagree with one another's answers to

Leslie's question. This lack of conflict and the students' acknowledgement of their peers' contributions show this to be a consonant interaction style.

5.7.4.3 Discursive dimension

The discursive dimension of the Building Understanding towards an Answer Mode is characterized by elaborative interaction patterns. All students participating contribute substantively to the conversation, and they explicitly connect their ideas to those put forth by other students. In the example, Leslie, Ben, and Ron all make substantive statements. In line 1, Leslie asks a question to the group about a relevant physics concept. In lines 2-5, Ben provides his thoughts on this concept, making use of a previous example and his understanding of it. In lines 6-7, Ron shares his own reasoning regarding the topic of Leslie's question. Not only do all three students contribute substantively to the discussion in this way; they also make explicit connections across their contributions. In lines 2-5, Ben directly relates his answer to Leslie's preceding question, and in lines 6-7, Ron explicitly connects his answer to Ben's by stating that it is "in other words". The substantive contributions the students make and the way that they connect them indicate that this conversation has an elaborative interaction pattern.

5.7.4.4 Disciplinary content dimension

The disciplinary content dimension of the Building Understanding towards an Answer Mode is described by abstract physics content. While the students in this context ultimately aim to produce an answer to a question, when they engage in the Building Understanding towards an Answer Mode, they do not focus on this goal directly. Instead, they discuss physics concepts in the abstract or general cases, first establishing an understanding of these before attempting to apply them in the creation of an answer to a particular question. In the example, the students attempt to arrive at an understanding electric potential energy in general and how it relates to electric field lines. In line 1, Leslie begins the episode with a question about the meaning of electric potential energy. Her question isn't directly related to determining an answer to the current question of the activity. When Ben responds in lines 2-5, he makes reference to a previous problem the students had completed, but does not attempt to connect it to producing an answer to the current question. In Ron's response in lines 6-7, he provides his understanding of electric potential energy, again, not connecting it to answering the current question in the activity. As the focus of their conversation was not the production of an answer, but instead the meaning and relationships among the concepts involved, their conversation is characterized by abstract physics content.

5.7.5 Relationships Among Modes

The four Modes of Collaboration defined here can be distinguished from one another along the three dimensions (see Table 5.2).

In addition to considering each Mode independently as above, it can be illustrative to consider the similarities and differences among them. One element to consider is the number of participants each Mode tends to have. The Debate Mode is the only Mode which has a specific number of participants – two. Informing, Co-constructing an Answer, and Building Understanding towards an Answer all may have any number of participants (greater than one). The Debate Mode is also unique from the other three Modes in that it is the only one to take place with a dissonant interaction style in the social dimension, while the others have a consonant interaction style.

Co-constructing an Answer and Building Understanding towards an Answer are perhaps the most similar Modes; they both have elaborative interaction patterns in the discursive dimension and consonant interaction styles in the social dimension. Even in the disciplinary content dimension, both Modes ultimately seek to produce answers to the questions in the activity. The crucial distinction between them is the way in which the students go about producing those answers. To illustrate this difference, a continuation of the transcript in Episode D is presented here, in which we see a switch from Building Understanding towards an Answer to Co-constructing an Answer. The fourth member of the group, Donna, who did not participate in Episode D, begins participating here.

5.7.5.1 Episode E

Leslie: Okay, but then looking too, [gesturing at the image] so this has a large radius away from this section, and it also has like a similar density of lines and like really close to here. So since they the same density of lines and this is a bigger radius, would this be more potential energy?

Donna: Well, okay, if you look at like the original lines [gesturing at the image] and the arc length between those, as they get farther out, that shows like… but they added lines in here. I don't know why they did that. But, like that line's kind of added in there. It didn't start from the beginning.

Ben: [speaking while Donna continues] Yeah.

Donna: This line goes from the beginning.

Ron: [speaking while Donna continues] Mmmhmm.

Donna: That line goes from the beginning.

Leslie: Ohhh. That's confusing, cause then that's not like…

Donna: [inaudible] so maybe that's not the same thing.

Ben: I don't think that's related to [energy]… is it?

Leslie: Related? What do you mean? [looks at Ben]

Ben: I was thinking like if I were to like just go this distance [gesturing at the image], like anything... anything in this area would have a greater electric potential energy than like something [gesturing at another area on the image]

Donna: Maybe the equipotential lines would have been better.

Ben: Yeah.

Ron: [inaudible] So where is that? So it would be over the center? Not dead center. [miming being away from the center with his hand]

Donna: We could just say the origin of the arrows.

Ron: Yeah, the origin of the lines.

Leslie: Yeah.

[all begin writing on their worksheets]

In contrast to the focus on abstract content in lines 1-7 (discussed in the Building Understanding towards an Answer: Disciplinary Content Dimension section), in lines 8-11, we see Leslie shift the focus of the discussion to the image of the charge distribution from the activity question. Furthermore, her question makes a comparison of the magnitude of the electric potential energy at two points in the image. This is directly related to answering the activity question, which asks the students where the maximum magnitude of electric potential energy in the image occurs. When Donna responds in lines 12-19, she also refers to the image from the activity, and in lines 24-26, Ben discusses relative amounts of electric potential energy at different points in the image, again related directly to answering the activity question. Finally, in lines 29-34, the students explicitly discuss what to write as their final answers on their worksheets, and then do so.

The explicit focus on answering the activity question seen in Episode E indicates that the students are engaging in the Co-constructing an Answer Mode. This is notably different than the Building Understanding towards an Answer seen in Episode D, in which the students instead focused on establishing an understanding of the relevant physics concepts. Episodes D and E also demonstrate the relationship between Building Understanding towards an Answer and the production of an answer to an activity question. In Episode D, the students did not focus directly on producing an answer, but the results of the understanding they had built were later applied to answering an activity question.

Finally, episodes D and E indicate that shifts between Modes might be readily identifiable. Between lines 7 and 8, there was a clear change in the focus of the conversation, which showed a change in the Mode. That the four Modes of Collaboration observed in this context can be defined using the social, discursive, and disciplinary content dimensions, and meaningfully distinguished from one another makes them a framework that could be productively applied to acquire insights not offered by other frameworks, which will be explored in the Discussion.

5.8 Discussion

The Modes of Collaboration can offer a perspective not provided by existing frameworks, but shares elements with and is greatly informed by previous work regarding student group dynamics in physics and other disciplines. In particular, the three dimensions that are used to define the Modes are closely tied to previous work. The social dimension rests on the interaction styles identified by Lumpe and Staver [21], the discursive dimension makes use of the interaction patterns identified by Hogan et al. and argumentation as conceived of by Toulmin [128, 175], and the disciplinary content dimension bears similarity to the work on epistemic framing by Irving et al. [125].

The relationship of the Modes of Collaboration framework with the work on epistemic framing by Irving et al. merits particular discussion, as this relationship may be the least clear. The expansive vs narrow axis defined by Irving et al. clearly has a relationship to the abstract and specific content distinguished in the disciplinary content dimension of the Modes; both are related to the degree to which student talk is directly tied to the task on which they are working. While the Modes solely attend to whether or not students are focusing on producing an answer to make a distinction between abstract and specific content, however, that is only one piece of evidence that Irving et al. make use of in their characterization of student discussion on the expansive vs narrow axis. For example, they also consider aspects such as the use of multiple representations to indicate a more expansive framing, and an extended focus on answering an instructor's questions to indicate a narrow framing. In this way, the narrow vs expansive axis is more broadly defined and inclusive of more elements than the abstract and specific physics content distinguished in the disciplinary content dimension. It is also worth noting that the Modes are fundamentally different than the framework for epistemic framing developed by Irving et al. in that they have different goals. The Modes of Collaboration seek to holistically consider and distinguish different types of student interactions in groups based on their behavior, while Irving et al.'s epistemic framing aims to describe how students appear to frame the activity in which they are engaged. To identify a group as engaged in a particular Mode is to describe how they are interacting with each other. This is not necessarily the same as stating that all the students are framing the activity in the same way. One could imagine different students framing a Debate quite differently, for example. Some may see it as a positive manifestation of academic rigor, while others may feel that it is undesirable conflict. In this way, analyzing student behavior through the work on epistemic framing by Irving et al. and using the Modes of Collaboration to identify how students are engaged in group work are separate endeavors.

More generally, the Modes of Collaboration framework is set apart from the previous work on which it builds in that it makes use of the constructs developed by the aforementioned authors simultaneously in the analysis of student interactions, and in a way that distinguishes the social, discursive, and disciplinary content related elements. These three dimensions each carry valuable information on student engagement, and by attending to all three, none of that information is neglected. For example, if one only considered the social and disciplinary contentment dimensions, Informing and Co-construction of an Answer would not be distinguishable, as they are both consonant and focused on specific content. However, to an instructor or researcher, the difference between one student instructing their group on the correct answer, and multiple students working as peers in the development of an answer, can be of great importance.

In addition to retaining the information carried by all three dimensions by attending to them simultaneously, the Modes of Collaboration framework attends to them independently. The framework does not make any a priori assumptions about the relationship between the dimensions, and so analysis along one dimension is not used to inform analysis along the other dimensions. This allows for the possible identification of Modes that may have been neglected had such relationships been assumed. For example, while we did not observe an episode with consonant social interaction and argumentation as its discursive dimension, and such a pairing may seem unlikely, the Modes of Collaboration does not discount its possibility. Attending to the dimensions independently also makes the framework relatively simple to apply, and suitable for multiple types of analyses. One does not need to consider the convolution of the dimensions in identifying Modes, as episodes are categorized along each dimension separately. Once the Modes present have been identified, one could use this data to analyze a snapshot of a single group, compare the Modes present across multiple groups, or consider the Modes a single group engages in over time.

This multi-dimensional approach has benefits when compared to frameworks that focus on a single area. For example, Toulmin analysis focuses on the content and structure of speakers' discourse. Applied in our context, it would be very successful in describing how students constructed their arguments. One thing it would not attend to, however, would be the type of physics the students discussed. A Debate on specific content and a Debate on abstract content would be treated the same. The multi-dimensional approach used in our framework captures these differences, which can be crucial for understanding the variety of ways that students experience group work.

While the Modes of Collaboration framework is able to provide a unique and productive description of student engagement with group work, it is not an all-encompassing description. Of the video analyzed once moments with off topic conversation or no explicit interaction had been neglected, 68% was identified as being an instance of a Mode. Thus the Modes defined here do not completely describe the possibilities of student interactions. Common interactions not classified as Modes in our data included students confirming how to phrase their answers on their worksheets, and sequences of disconnected statements.

The small number of students and relatively short amount of time analyzed in our data naturally limits the degree to which the Modes might be generalizable. Because the students in our data worked on a single activity, the Modes we observed may have been influenced by that activity. Specifically, the fact that the task required the students to produce answers to turn in on a worksheet may have fostered an environment which favored Modes that focus on the construction of an answer. It is also possible that there is a relationship between the particular physics content in the activity and the Modes in which the students engaged. The highly abstract nature of electric field and potential energy may have prompted students to engage in different Modes than they might if the activity focused on a more familiar or concrete area, such as projectile motion. Additionally, the classroom in which our data was collected was facilitated with very minimal instructor interaction. It could be that with more active facilitation, or with certain types of facilitation, the Modes observed may vary.

There are other facets of the Modes that may exist, but that we simply did not observe due to our context or the small size of our data. For example, the Co-Construction Mode as observed in this context was specifically the Co-Construction of an Answer. It is possible that other "products" than an answer may be possible in the Co-Construction Mode, such as calculations or responses to instructor questions. The Debate mode may appear differently in other data, as well. In our context, we only observed Debates between two students, but it is conceivable that a Debate could have more than two students, all arguing unique perspectives, or even that "teams" could form, with multiple students arguing for one perspective and multiple students arguing for another.

Another manifestation of the Modes of Collaboration that may exist, but that we did not observe, is the co-occurrence of Modes. As all of the Modes may have as few as two participants, it is possible that in a group of four, dyads could form and simultaneously engage in different Modes. In our data, when only two students in a group of four participated in a particular Mode, the other two students were not identified as participating in any Mode. They were either quietly observing the two active students, or it was unclear on what their attention was focused. One could imagine, however, that two students in a group could engage in one Mode, while the other two students simultaneously engaged in another. For example, two students could engage in a Debate while the other two students in the group engage in the Co-Construction of an Answer. We did not observe such an episode in our data, but the Modes of Collaboration framework does allow for such an event.

Though it of course cannot describe all of student interactions, the Modes of Collaboration framework shows promise for being a useful tool for instructors. A simple implementation could be identifying which students are participants in episodes of Co-construction of an Answer or Building Understanding towards an Answer and using this as a way to consider how engaged different students are with their work. The Modes may also offer one way to identify if and how students alter their interactions with each other after an intervention by an instructor. Finally, the Modes of Collaboration framework may be useful in comparing how students engage with different facilitation techniques and different activities. Considering the Modes students engage in across such different contexts could provide better insight into the impact that different instructional choices have on student engagement with group work.

As interactive instruction continues to gain popularity, it is essential that instructors and researchers understand how students engage in such activities. The Modes of Collaboration provide a framework allowing insight in this area. The social, discursive, and disciplinary content dimensions on which the framework is based allow it to capture elements of student engagement that other frameworks may not, and also give it the flexibility to be adapted for cross-contextual analysis of different learning environments. This kind of analysis will be crucial for understanding the inherently complex and varied nature of collaborative learning environments and for ultimately providing students with the best opportunities for learning.

Chapter 6

Conclusions

6.1 Summary of findings

The motivation of this dissertation was to better understand the complexity of collaborative learning environments in introductory physics. We accomplished this by examining these learning environments from the perspectives of both instructors and students, and by considering expanding scopes of analysis.

In the most narrowly focused study, we considered the instructor perspective, examining the teaching approaches of learning assistants in a problem-based learning course, and specifically their approaches to teaching computational problems. We found four different approaches that learning assistants took, with the approaches representing increasing levels of sophistication in their perceptions and treatment of the computational problems. This result has implications for the way we train learning assistants and what factors may impact their teaching practices and beliefs.

Broadening slightly to consider the student perspective, but maintaining a relatively narrow focus by limiting its scope to conceptual reasoning, the second study investigated how groups of students reason in collaborative learning environments in physics courses. Using the construct of epistemic games, we identified a new group epistemic game, the shared answer-making epistemic game. Based on a previously identified individual epistemic game, the shared answer-making epistemic game is comprised of both individual and group level moves describing the way students were observed to reason through or intuit their way through conceptual problems. This result gives insight into how students may engage with activities depending on their design, and indicates that individual epistemic games may be expanded to describe similar observations of groups.

With the broadest scope, the third study considered the student perspective of collaborative learning environments, but expanded to consider elements of their experiences beyond their conceptual reasoning about the physics content. We developed a new framework, the Modes of Collaboration, for understanding student engagement with collaborative learning environments that attends to not only the disciplinary content of their discussions, but also the structure of their discussions, and the tone of their interactions. The Modes of Collaboration framework gives insight into multiple aspects of students experiences when working in groups and is flexible enough to be applied across collaborative learning environments, making it useful for practical applications in assessing and designing instruction and activities.

6.2 Implications and future directions

All three of the studies presented in this dissertation have practical applications for improving introductory physics courses and also suggest future areas of research.

The learning assistant approaches to teaching computational problems identified here can be used to make informed changes to the training and on-going support they receive. It's possible that explicitly discussing the intended purpose of the computational problems during training or during the weekly pre-class meetings could encourage learning assistants to adopt more sophisticated approaches. Supporting learning assistants in this way could have benefits for not only their development as teachers, but could also ensure that their students are receiving the computational experiences that the course intends they have. There are several open areas that would benefit from further research regarding this project. Given that the learning assistants' approaches in this study were largely uncorrelated with their levels of experience, it would be interesting to track their approaches longitudinally, to see what affects an individual's progression or lack thereof through the different approaches. For example, it is possible that the faculty members a learning assistant works with are important to the approach they take, or that their own ensuing experiences with computation affect their approach. It would also be informative to investigate if learning assistants teaching in a problem-based learning course on a different topic presented similar approaches to teaching computational problems, or if learning assistants teaching in a laboratory or more traditionally taught course presented similar approaches, to investigate to what degree the approaches identified here are contextual. One could also analyze in-class observations of learning assistants' enacted teaching practices to see if they align with their self-described approaches. Additionally, as a part of this study, interviews with several faculty members and a graduate teaching assistant were also conducted. Comparing learning assistants' approaches to teaching computational problems to those of graduate teaching assistants and faculty members could give more insight into how and why these different populations teach the computational problems differently or similarly. In particular, one interviewee was a developer of the course, and it would be interesting to compare his beliefs regarding the purpose of computation in the course to the learning assistants' approaches, since the intent is that the learning assistants teach in ways that are aligned with the goals of the course's developers.

The shared answer-making epistemic game can give insight into what factors might lead students to engage in more reasoning versus more intuition, and instructors could use this to inform how they design their activities depending on the type of conceptual engagement they wish to encourage. It also could give instructors insight into how their students navigate conflicting understandings when collaborating, and how they might be able to make such conflicts productive for students' learning. Related to this, one opportunity for further research on this project would be investigating what happens if no student induces a disruption to a group's progression through the game. It could be that such disruptions are important in encouraging students to fully articulate their ideas to each other, and analyzing the work of a group that experiences no disruption could provide insight into this issue. It would also be informative to examine if the shared answer-making epistemic game appears in the same way or at all when students work on a less abstract concept than electric field. Student confidence or familiarity with the concepts being probed could affect the degree to which they rely on their intuition as opposed to conceptual reasoning, and investigating students' work on a different subject could shed light on this issue. A study such as this, or a study examining the work of students in a more closely facilitated learning environment could also indicate what elements of the shared answer-making game were tied to our context.

The Modes of Collaboration framework can be applied across learning contexts and activities, and provides instructors with a simple tool to identify how their students are engaging with one another while collaborating. By assessing how their students collaborate in different situations, the framework could allow instructors to make choices regarding activity design, interventions, and group formation that encourage the types of interactions most aligned with their goals. The flexibility of the Modes of Collaboration framework also opens up several new areas of investigation. Examining which Modes students use in a more carefully facilitated collaborative learning environment could give insight into what impact the different facilitation styles have on their engagement. In fact, the Modes of Collaboration framework was applied to a small amount of data from a problem-based learning course, and preliminary analysis suggested that students did not engage in the same Modes at the same rates, and that there were likely entirely new Modes present. In addition to comparative studies like this, a longitudinal study examining which Modes of Collaboration a group of students uses over the course of a semester could help us understand how students' learn to collaborate and what affects that process.

6.3 Concluding remarks

As undergraduate physics education continues to transform to better meet the needs of students and society, collaborative learning environments will play an important part. As more instructors and students find themselves in these learning environments, we will need to be able to make informed decisions about their design and implementation to best provide students with experiences and skills that will serve them in their continuing studies and careers. By understanding the many facets of these environments, we can create learning environments in introductory physics that will help our students develop as learners, scientists, and scientifically literate members of society.

APPENDICES

Appendix A

Expanded description of phenomenographic analysis

This appendix presents a more detailed description of the analysis conducted for the study presented in Chapter 3. As described in Chapter 3, the study examined learning assistant approaches to teaching computational problems in a problem based course, specifically employing phenomenography as the method.

Goals of a phenomenographic study

Phenomenography rests on the assumption that although individuals experience a given phenomenon in unique ways, by probing a group of individuals' experiences of the phenomenon, a set of categories can be developed that describe the different ways people experience the phenomenon. The goal then of a phenomenographic study is to find the most concise set of categories that capture the essential variations in individuals' experiences of the phenomenon. A phenomenographic study does not seek to account for the entirety of a given individual's experience of the phenomenon, nor does it seek to develop categories that allow for each individual to be unambiguously sorted. Instead, the objective is to use the individuals' experiences to identify themes in what people experience regarding the phenomenon, and variations in how they discuss those themes. It is these variations that allow meaningful categories to be developed that capture the essential differences in how people may experience the phenomenon [54, 137, 154, 155, 158, 159]. In order to draw a rich description of individuals' experiences with the phenomenon of interest, phenomenographic studies often use interviews as their data source. Phenomenographic interviews are typically semi-structured, with the interviewer having a set of topics or questions they wish to address, but allowing for the conversation to follow tangents that arise [159, 167–169].

Phenomenographic methods applied to learning assistant approaches to teaching computational problems

Data collection and reduction

Such interviews were conducted for the study presented in Chapter 3, surrounding the phenomenon of interest: approaches to teaching computational problems. The interviews were audio and video recorded, and the audio recordings were sent to an external company for transcription. Once the interview transcripts were received, analysis began with reviewing all the transcripts several times in order to become familiar with the data set as a whole. After gaining familiarity with the full data set, the data was reduced based on relevance to the phenomenon of interest. Because the interviews were open to following tangents, and because several background questions were asked (see Appendix C), there were portions of the transcripts that were not relevant to the participants' experiences with teaching computational problems. For example, participants may have discussed their motivations for becoming learning assistants, or described their teaching explicitly with respect to analytic problems. In an example of the latter, one learning assistant spoke about teaching the analytic problems, which occur on Tuesdays,

> On Tuesday, the first question I'll ask them is, "What do you ultimately need to get? Where is your end goal?" They say, "Oh, this is our end goal." "Okay, what are the steps you need to take to get that?" That's on a Tuesday.

Portions of transcript such as these were neglected for the thematic analysis described next since they were not directly relevant to our phenomenon of interest, but they were retained in order to provide fuller context for participants' comments if necessary.

Identification of preliminary themes

Once identified, the reduced data set was analyzed for emergent themes in participants' discussion of teaching computational problems. These themes represented trends and common threads in what the participants spoke about over the course of the interview. Some of these themes corresponded to questions that were directly asked by the interviewer, while others did not. In either case, the themes were identified based solely on the comments of the participants in the transcripts, and the researchers strove to analyze the transcript without bias towards any particular themes emerging. This process resulted in a preliminary set of seventeen emergent themes shown in Table A.1. These themes do not account for all of the reduced data set. Some relevant portions of transcript were too unique or specific to be sorted into a theme. Examples include a learning assistant speaking on very specific role that he plays as computation expert on computation days, or extra preparation that a learning assistant engages in before she teaches computational problems. While these comments were interesting, they were not further analyzed. Since the goal of this study, and of any phenomenographic study, is to find the most concise way to capture the different ways that

Preliminary Themes
Differences between analytic and computational teaching
Written feedback
Varying levels of student programming experience
Different student approaches to computation
Differences in student behavior solving computation versus analytic problems
What students should do when solving computation problems
Acceptable places to end computation days
Minimally working programs
Solution manuals
Why code in groups
Student challenges
Teaching challenges
Teaching physics versus teaching coding on computation days
In-class teaching strategies
Important things for students to take away
Purpose of computation
Student frustration

Table A.1: List of preliminary emergent themes identified in the data

individuals may experience a phenomenon [54, 137, 158, 159], it is expected that not every relevant comment from the participants will be identified as belonging to a theme.

It is also worth noting that these themes are not necessarily mutually exclusive, and that there are portions of transcript that were coded as belonging to multiple themes. This is because in a given comment, a participant often discusses several dimensions of their experience at once. Thus one would not expect, and it is not a requirement that the themes be wholly orthogonal.

Analysis of preliminary themes

Once preliminary themes had been identified, individual themes were selected and examined in more detail to identify the variations in how the learning assistants discussed them. This analysis began with the investigation of the themes that were most richly populated,

Preliminary Teaching Technique Variations
Focus on navigating programming errors
Encourage reflection on coding
Use the same techniques on analytic and computation days
Attend to course design considerations on computation days
Don't let programming details become a distraction
Leverage affordances of computational problems

Table A.2: List of preliminary variations within the *teaching technique* theme

Preliminary Teaching Goal Variations
Building student independence
Encouraging computational norms
Supporting content learning
Encouraging reflection on learning and process
Ensuring group has consensus
Maintaining positive student attitudes
Getting students through the problem

Table A.3: List of preliminary variations within the *teaching goal* theme

and which had the strongest apparent tie to our phenomenon of interest. These themes were *in-class teaching strategies*, *differences between analytic and computational teaching*, and *teaching physics versus teaching coding on computation days* as all three had explicit references to how learning assistants teach in the classroom. Through the process of identifying emergent variations within these preliminary themes, the themes were reorganized into two themes: *teaching technique* and *teaching goal*. These two themes and their variations are shown in Table A.2 and Table A.3.

The identified variations were split into these two themes because it was observed that those in Table A.2 represent specific teaching moves, while those in Table A.3 relate to broader motivations the learning assistants had regarding their teaching. The relationship between these two themes will be addressed in greater detail later in this appendix.

The next preliminary theme to be analyzed was *important things for students to take*

Preliminary Teaching Outcome Variations
Programming skills
Physics understanding
Translating physics to code
Seeing physics concepts in code
Translating physics to visualizations
Capabilities of computation

Table A.4: List of preliminary variations within the *teaching outcome* theme

away, which was found to have the variations listed in Table A.4. Based on the variations identified, the theme was retitled *teaching outcome*, since it was observed that the variations all related to the outcome the learning assistants desired for their students.

At this point in the analysis, these three preliminary themes and their variations were presented to a team of researchers for feedback and critique. A major finding from this was that it was difficult to articulate what the difference between the *teaching outcome* and *teaching goal* themes was. While it was initially argued that the former referred to tangible outcomes for students, and the latter referred to more general motivations of learning assistants, it became clear that based on the relevant portions of transcripts and discussion amongst researchers, such a distinction was not always observable.

First refinement of themes

Based on the aforementioned feedback, the variations in Tables A.2, A.3, and A.4 were considered holistically, with an eye for themes that would better capture the commonalities and differences among them. This resulted in a new organization comprised of three themes and their respective variations indicated in Tables A.5, A.6, and A.7. This restructuring retained elements of the original organization, while also making several important changes.

The *teaching outcome* theme underwent the least change, as seen in Table A.5. Three of

Refined Teaching Outcome Variations
Programming skills
Physics understanding
Physics-code connection
A new approach to learning
Capabilities of computation

Table A.5: First refinement of variations within the *teaching outcome* theme

Teaching Strategy Variations
Focus on navigating programming errors
Encourage reflection on coding
Use the same techniques on analytic and computation days
Leverage collaboration
Leverage affordances of computational problems in teaching

Table A.6: List of variations within the *teaching strategy* theme

Characteristic to Moderate Variations
Student attitudes
Student attention to programming details
Student work pace
Impact of course design

Table A.7: List of variations within the *characteristic to moderate* theme its initial variations (*programming skills*, *physics understanding*, and *capabilities of computation*) were unchanged. The other three initial variations (*translating physics to code*, *seeing physics concepts in code*, and *translating physics to visualization*) were merged into a single new variation, called *physics-code connection*. Because our goal was to ultimately develop a set of categories of description that captured the *essential* differences in how learning assistants approach teaching computational problems, we argue it is not essential to separate these three initial themes. All three are related to students seeing relationships between the physics concepts and the computational representation of them, be it lines of code or resulting visualizations. Furthermore, the difference across these three initial variations is very small in magnitude when compared to their collective differences from the other variations. That is, there is a greater difference between a student gaining an understanding of the capabilities of computation and a student learning to translate physics to code than there is between a student learning to translate physics to code and a student being able to see physics concepts in code. For these reasons, the three initial variations were merged into the single *physics-code connection* variation. The final change to the *teaching outcome* theme in this stage of the analysis was the addition of a new variation: *a new approach to learning*. This variation was comprised of two variations that were formerly in the *teaching goal* theme, *building student independence* and *encouraging reflection on learning and process*. These were merged because they both address elements beyond content understanding or even reflection on physics or computation. Instead, they discuss learning strategies and approaches that are broadly applicable, not tied directly to the context or content of the course. This new variation was then moved to the *teaching outcome* theme because the relevant transcript indicated a focus on what the learning assistants wanted their students to gain or take away from the experience, and thus constituted an outcome.

The changes to the *teaching technique* and *teaching goal* themes were more extensive. As stated previously, a major motivation for the refinement carried out in this stage of analysis was a difficulty in arguing the delineation between these two themes. It became clear that it was not possible to distinguish between the two themes as they had been defined. Instead, two new themes emerged that were better able to capture differences among their collective variations. One of these new themes was named *teaching strategy*. This theme refers to the ways learning assistants describe their teaching moves. It is similar to the former *teaching technique*, however its definition does not depend to a particular scale of teaching act. Instead, the *teaching strategy* theme accounts for both very specific moves and also larger scale teaching methods. The variations within the *teaching strategy* are shown in Table A.6. As indicated in the table, four of the variations are those formerly found in the *teaching technique* theme, and one is a new variation called *leverage collaboration*. This variation was formerly titled *ensuring group has consensus*, and belonged to the *teaching goal* theme. Upon closer inspection of the transcript, it was determined that the variation was not always specifically aimed at simply making sure a group of students agreed with each other, but also included other methods of utilizing the group-based nature of the course in teaching. Because of this, it was retitled *leverage collaboration*, and it was moved to the *teaching strategy* theme, because it represented a method of teaching in the course.

The final element of this stage of analysis was the identification of a wholly new theme: *characteristic to moderate*. This theme was comprised of variations from the former *teaching technique* and *teaching goal* themes that were identified as not really being about teaching methods or outcomes, but were instead related to what on-going aspects of their students' work learning assistants feel they must monitor and influence. These variations (with slight name changes) are indicated in Table A.7, and demonstrate this focus. In particular, when considering Tables A.6 and A.7 together, one can see that the variations within the former represent methods of teaching, while those in the former represent on-going elements of a group's work to moderate.

With this new thematic organization developed, analysis continued on the remaining preliminary themes in Table A.1.

Continuing analysis of preliminary themes

The next preliminary theme to be analyzed was *purpose of computation*, because it was hypothesized that a learning assistant's perception of the usefulness of computation would have a notable effect on their teaching. Table A.8 shows the variations identified within the *purpose of computation* theme. After this, the *student frustration* theme was analyzed for variations, because it was suspected that it may be accounted for already by the *student attitudes* variation of the *characteristic to moderate* theme. This was found to be largely correct, and the majority of the portions of transcript in the *student frustration* theme not identified as *student attitudes* were nonetheless accounted for by variations within the already identified themes. For example, learning assistants would discuss student frustration in the context of how it leads them to encourage reflection on coding, a variation from the *teaching strategy* theme. The only type of comments in the *student frustration* theme not accounted for by existing variations within other analyzed themes related to the benefit that the challenge presented by coding problems provided students by giving them practice with overcoming struggles. This class of comments was titled *students learn to overcome struggles*, and was categorized as an additional variation within the *purpose of computation* theme, since similar to several other variations seen in Table A.8, it represents a perceived utility of the computational problems.

Preliminary Purpose of Computation Variations
Visualization helps students check solutions
Computation days require students to interact with concepts multiple times
Computation shows the effects of making changes easily
Programming is an important skill
Computation helps solve problems
Visualization helps show physics concepts
Students learn to work together effectively
Computation teaches one to think differently

Table A.8: List of preliminary variations within the *purpose of computation* theme

At this point in the analysis, the *purpose of computation* theme was split into two more specific themes: *utility of computation* and *benefit of computation in P Cubed* based on whether the described purposes related to the general usefulness of computation, or to the advantages it provided students in the course. This separation is show in Tables A.9 and A.10. The variations indicated in Table A.9 represent learning assistants' perceptions of the general applicability or purpose of coding, not simply in the classroom. For example, they regard programming's general importance in modern working society, or its usefulness in carrying out science by helping to solve difficult physics problems. On the other hand, the variations shown in Table A.10 are related to the positive aspects of incorporating computation into the classroom specifically. For example, noting that students learn to work together better on computational days, or discussing how computational days require students to use the concepts from analytic days an additional time. One additional modification made at this stage in analysis is that *visualization helps students check their solutions* and *computation shows the effects of making changes easily* variations were combined into a single variation called *visualization provides students immediate feedback*. This was done because both initial variations referred to ways in which the computational problems allowed students to get information quickly regarding their solution, whether it be checking correctness, or

Utility of Computation Variations
Programming is an important skill
Computation helps solve problems
Visualization helps show physics concepts
Computation teaches one to think differently

Table A.9: Variations within the *utility of computation* theme

Benefit of Computation in P Cubed Variations
Visualization provides students immediate feedback
Computation days require students to interact with concepts multiple times
Students learn to work together effectively
Students learn to overcome struggles

Table A.10: Variations within the *benefit of computation in P Cubed* theme

investigating the effects of making various changes. The difference between these two initial variations was small compared to their differences from the other variations, and so they were merged to provide a more meaningful set of variations.

We will note here that not every variation was easily identified as belonging in *utility of computation* versus *benefit of computation in P Cubed*, and will return to this point later in this appendix. However, the five themes identified thus far (*utility of computation*, *benefit of computation in P Cubed*, *teaching outcome*, *teaching strategy*, and *characteristic to moderate* were used for the next stage in analysis.

Development of preliminary categories of description

The five themes defined thus far were then considered holistically. The goal of a phenomenographic study is to develop categories of description which capture the different ways individuals may experience the phenomenon of interest. This is done by looking across themes and identifying which variations when considered together describe a logically coherent way to experience the phenomenon. It is important to note that categories are not developed on the basis of examining which variations cooccur in individuals. Instead, the goal is develop categories that represent holistic experiences of the phenomenon that highlight the essential differences uncovered in the data [54, 137, 158, 159]. With this goal in mind, we considered the variations seen in the five themes analyzed thus far. This was done at this point in analysis because the five themes indicated a rich variation in experiences teaching computational problems and provided a great deal of information with which to develop preliminary categories of description. Furthermore, the data analyzed thus far represented a great majority of the reduced data set to be considered. Based on these considerations, it was decided that it was an appropriate point at which to begin developing categories of description by looking across the themes and variations defined thus far.

The first decision made in this stage of analysis was to remove the *use the same techniques on analytic and computation days* variation from the *teaching strategy* theme, and to remove the *physics understanding* variation from the *teaching outcome* theme. In both cases, this was done because the variations were not useful in developing categories that described different ways that learning assistants approached teaching computational problems. As it was a physics course, it is not surprising that every learning assistant discussed physics understanding as their desired teaching outcome to some degree. Thus this variation did not provide useful information. Instead, the remaining variations in the *teaching outcome* theme were more meaningful in identifying differences in the learning assistants' experiences. Similarly, every learning assistant discussed using at least some of the same teaching strategies on both analytic and computational days. This is also not surprising, as the computational days are not meant to be completely different experiences for the students. The learning assistants are aware that P Cubed encourages certain types of teaching and learning regardless of the type of problem being solved that day, and so there were none who claimed to not use

Category of Description	Utility of Computation	Benefit of Computation in P Cubed	Teaching Outcome	Characteristic to Moderate	Teaching Strategy
Narrow programming focus	Programming is an important skill	Visualization provides students immediate feedback	Programming skills	Student work pace	Focus on navigating programming errors
Learning physics via computation focus	Visualization helps show physics concepts	Students are required to interact with concepts multiple times	Physics-code connection	Impact of course design	Leverage affordances of computational problems
Computation as a scientific tool focus	Computation helps solve problems	Students learn to overcome struggles	Capabilities of computation	Student attention to programming details	Encourage reflection on coding
Shifting perceptions of learning focus	Teaches one to think differently	Students learn to work together effectively	A new approach to learning	Student attitudes	Leverage collaboration

Table A.11: Preliminary categories of description

any of the same strategies on analytic and computational days. This made this variation unproductive when looking for differences across learning assistants' experiences, and so it was removed from the *teaching strategy* theme. Having made these two cuts, the first set of categories of descriptions were developed, shown in Table A.11. The second through sixth columns of the table represent the five themes considered at this stage in analysis, with their respective variations appearing as one looks down each column. The first column indicates the name of each preliminary category of description. Each category of description is defined by one variation within each theme, thus the *narrow programming focus* category is described by the variations indicated by looking across the rest of the second row.

In phenomenographic studies, the categories of description are formed by looking across the themes identified in the data, seeking to group them in ways that indicate a cohesive way to experience the phenomenon of interest [54, 137, 158, 159]. In our case, we sought to identify coherent categories that would describe a learning assistant's approach to teaching computational problems. As such, this stage of analysis constituted a sort of secondary thematic analysis, where we now analyzed the variations for emergent threads that describe a coherent approach to teaching computational problems. As indicated in Table A.11, four preliminary categories were developed. As these categories were only slightly modified before being finalized, they will be described briefly here, with a fuller explanation of their development appearing in the "Final categories of description" section of this appendix.

The *narrow programming focus* category was developed around an emergent thread found in the identified variations, and this thread related to a learning assistant having a relatively limited view of computation's purpose and what computation is. With this focus, computation is viewed largely to be the act of using programming syntax, and there are few explicit connections drawn between computation and learning or computation and science.

The *learning physics via computation focus* was developed around an emergent thread wherein a learning assistant treats computation as primarily a pedagogical tool. Computation is seen as a useful way to learn physics concepts in a classroom setting, however there are few connections made to its usefulness in practicing physics or science outside of the classroom.

The *computation as a scientific tool focus* was developed around variations that indicated an emphasis on computation as a tool used in the practice of science. With this focus, computation is treated as an important part of carrying out science outside of the classroom, and is not viewed as only a learning aid.

The *shifting perceptions of learning focus* was developed around variations that focused on computation as a means to achieve goals beyond the scope of the classroom or even

Utility of Computation Variations
Programming is an important skill
Computation aids content learning
Computation makes difficult problems easier
Computation offers space for broader skills

Table A.12: Variations within the reorganized *utility of computation* theme

of science specifically. Instead, computational problems were treated as opportunities to engage students with broader skills and reflection on their own learning and problem-solving processes.

Based on the organization shown in Table A.11, several issues were identified with the preliminary categories of description. First, it was observed that a few variations did not have clear connections to their categories. In particular, in the *computation as a scientific tool focus* category, it was difficult to articulate the connection of the *students learn to overcome struggles* variation. As this category centers around an emphasis on the real-life usage of computation in science, the relationship that students learning to persevere in the face of difficulty had to this was not unambiguously clear. Second, as alluded to earlier in this appendix, it was not readily apparent which variations belonged in the *utility of computation* theme versus the *benefit of computation in P Cubed* theme. For example, the *visualization helps shows physics concepts* was at times used in reference to scientists using visualizations to predict difficult to observe phenomena, but at other times was used to refer to demonstrating difficult to understand concepts to students. Based on these two issues, the decision was made to remerge these two themes, retaining the name *utility of computation*, but no longer with a limitation on whether those utilities were classroom specific or more general. This new organization of these variations is shown in Table A.12.

To arrive at this organization of the theme, several variations were merged. *Visualization* *provides students immediate feedback*, *students are required to interact with concepts multiple times*, and the examples of *visualization helps show physics concepts* that were contextually bound to the classroom were merged to form the new variation: *computation aids in content learning*. This was done because all of those variations centered around computation's usefulness within the classroom, helping students learn physics concepts. *Computation helps solve problems* and the examples of *visualization helps show physics concepts* that referred to their use outside the classroom were merged to form the new variation: *computation makes difficult problems easier*. This was done because these variations both related to computation's utility as a tool for modeling and solving difficult problems outside of the classroom. Finally, *computation teaches one to think differently*, *students learn to overcome struggles*, and *students learn to work together effectively* were merged to form the new variation: *computation offers space for broader skills*. This decision was made because these variations all related to skills that students may develop through the computational problems that are not directly related to physics, science, or programming.

As described with respect to analysis decisions made earlier in the process, these decisions were all ultimately made in order to develop categories which captured the *essential* variations in how learning assistants approach teaching computational problems. Based on the initial categories of description identified, and the similarity of the themes and variations that were merged to create Table A.12, it was determined that, for example, the particularities of how learning assistants viewed computation aiding classroom learning were not as important as the difference between viewing computation as a pedagogical tool in general and viewing computation as a tool for problem-solving outside the classroom.

The final modification made to the preliminary categories of description was based on the determination that not all portions of transcript coded as belonging to the *computation* *as a scientific tool focus* had an explicit connection to the practice of science. Instead, they often focused more generally on computation's usefulness as a tool in approaching problems. To better reflect this, the category was retitled the *computation as a tool focus*, emphasizing computation as a way to approach difficult problems, rather than computation as a specifically scientific practice.

Having made these modifications, the categories were finalized, and will be described in the following section.

Final categories of description

Based on the final changes described, the final categories of description were developed, which appear in Table A.13. A full explanation of the development of the categories will now be provided.

Narrow programming focus

The *narrow programming focus* category is based around an emphasis on computation as the act of entering code. There is little reflection on how computation may be used in teaching or science, rather it is treated as a valuable but unconnected skill.

In the *utility of computation* theme, it is characterized by the belief that *programming is an important skill* to have in today's society, with very little elaboration or explicit reflection on why this is. For example, one learning assistant said,

> [Programming] has been really helpful in a lot of my different classes, and then also in my internship this last summer, just like as an engineering person in general. That's one thing that I try and stress to the students, is it's like, "Okay, you might think that you're never going to use this, but it's actually so helpful if you do know how to use even just a small portion of it."

Category of Description	Utility of Computation	Teaching Outcome	Characteristic to Moderate	Teaching Strategy
Narrow programming focus	Programming is an important skill	Programming skills	Student work pace	Focus on navigating programming errors
Learning physics via computation focus	Computation aids content learning	Physics-code connection	Impact of course design	Leverage affordances of computational problems
Computation as a tool focus	Computation makes difficult problems easier	Capabilities of computation	Student attention to programming details	Encourage reflection on coding
Shifting perceptions of learning focus	Computation offers space for broader skills	A new approach to learning	Student attitudes	Leverage collaboration

Table A.13: Final categories of description. The *narrow programming focus* treats the computational problems as a way to develop students' abilities to write code. The *learning physics via computation focus* treats the computational problems primarily as a means for learning physics concepts. The *computation as a tool focus* treats the computational problems as a way to help students understand the value of computation in modeling and solving problems. The *shifting perceptions of learning focus* treats the computational problems as opportunities to develop students' understandings of their own learning.

In this quote, the learning assistant describes how she tries to convey to her students that programming is helpful, noting that she has used it in multiple contexts. She discusses how she has used it inside and outside of the classroom, and references her background as an engineer. She does not elaborate on its importance in her learning or work, however, and she does not describe how or why it is helpful. Instead, she only states that students are likely to encounter it in other situations and that it can help them. This lack of reflection on *how* computation is helpful and relevant is an example of a learning assistant expressing a perception that the utility of computation is simply that *programming is an important skill*.

In the *teaching outcome* theme, the narrow programming focus is characterized by an emphasis on *programming skills*. That is, the learning assistant desires their students to gain an understanding of how to carry out programming tasks. One learning assistant said,

> If it's something where they added an object, or they were talking about an object, or coded in an object in their calculation loop, but never defined that object, then that's a place where it's like, "Okay, let's kind of go through this more line by line. What is this line telling us? Okay, where else does that object show up in the code? Wait, it doesn't show up anywhere else? We might need to address that." Because that is an understanding thing where they need to understand that they have to define something in the code before they can do anything to that object. You can't do something to an object that you don't have.

In this quote, the learning assistant discusses students facing an error resulting from referencing an object that they had not yet defined in their code, and states that is an error that she will intentionally target with her teaching. She goes on to say that she does this because the students "need to understand" the process of defining and calling objects in programming. Expressing a belief that her teaching should result in students knowing how to carry out elements of programming such as this indicates that *programming skills* are her desired teaching outcome.

In the *characteristic to moderate* theme, the *narrow programming focus* is characterized by *student work pace*. When moderating this characteristic, learning assistants attend to their students' rate of progress, seeking to ensure that students reach the end of the problem by the end of class. An example of this is given by a learning assistant who said,

> I might let them just mess with it for awhile. But it's sort of a time balance thing. So I've done these problems so many times, I know where they should be at certain times to make sure they finish, and so I usually let them mess with it until I think, "Okay, it's halfway through, they should be at this point. I'm gonna try to redirect them back to where they should be."

With this quote, the learning assistant indicates that regardless of the exploration she'll sometimes allow her students to do, she will take steps to ensure that they are able to finish the problem in the allotted time. She explicitly comments on using particular time markers to check on where students should be at different points in the class session. This emphasis on making sure students complete the problem indicates that she moderates *students' work pace*.

In the *teaching strategy theme*, the *narrow programming focus* is characterized by a focus on *navigating programming errors*. With this strategy, learning assistants focus their teaching on helping students identify and overcome programming errors in the traditional sense. That is, mistakes in their code that cause it not to function. One learning assistant employing this strategy stated,

> Most of the time, I just teach them how to do it because it's usually when they've just like edited like one line of code, and then it's like, "Oh, we have the tabbing error." I'll just be like, "Here's how you solve that: Highlight, and then do the thing, and then, yay, it's good." Then they'll be like, "Okay. Cool. Now I know how to do this in the future."

In this quote, the learning assistant describes a common error the students encounter: problems with their indentation. She explains that she tailors her teaching to this fact by preemptively instructing students on how to resolve that error. This emphasis on helping students handle errors of this nature demonstrates a teaching strategy that is focused on *navigating programming errors*.

When considered together, one can see how these variations come together to form a cohesive approach to teaching computational problems, and one that is focused on a narrow view of programming. With the belief that computation is essentially entering programming syntax, it follows that a learning assistant's desired teaching outcome would be those sorts of programming skills. Similarly, it follows that a learning assistant with this approach would employ a teaching strategy focused on navigating programming errors, because those errors represent the fundamental obstacles of computation when one views computation to be correctly entering code. The *narrow programming focus* corresponds to a belief that the utility of computation is simply that programming is an important skill. This aligns with a narrow understanding of what programming is, because without understanding there to be deeper connections between computation and science or learning, the usefulness of computation in P Cubed would simply be that students learn how to program. Finally, this approach is completed by a learning assistant moderating the pace at which their students progress through the problem. This corresponds to a narrow view of programming focus because again, without a reflection on computation as a pedagogical tool or a problem-solving tool, and with programming being the act of entering code, the "game" that students must play on computational days becomes merely to get properly working code. With this belief in mind, it follows that a learning assistant would want to ensure that their students complete the problem and arrive at a correct solution. All four of these variations therefore come together to illustrate an approach to teaching computational problems characterized by a narrow programming focus.

Learning physics via computation focus

The *learning physics via computation focus* is characterized by an emphasis on the computational problems providing a pedagogical tool that learning assistants may leverage in their teaching. Computation is perceived primarily as useful in the classroom to help students learn concepts.

In the *utility of computation* theme, the *learning physics via computation focus* is characterized by the belief that the value of computational problems is that they *aid students' content learning.* One learning assistant expressing this belief said,

> The students get to see it represented so it's kind of like a reward almost for writing out the code. They think if I do this it changes this and it's beneficial to see how ... For example, we did a problem with drag. So, it's good to see how drag affects this and if we increase the coefficient it'll do this and this. It's a good way they can input information and immediately see the results of how the physics is applied.

In this quote, the learning assistant expresses that he believes the usefulness of the computational problems to be their ability to help students better understand the concepts. Specifically, he discusses how students can use the immediate feedback that computation can provide as a means to see the impact of the different physics concepts they are learning, in this case, drag. This type of emphasis indicates a belief in the utility of computation being that it can *aid students' content learning.*

In the *teaching outcome* theme, the *learning physics via computation focus* is characterized by an emphasis on the *physics-code connection.* This refers to a desire for students to see and understand how the code and visualizations involved in computation relate to the physics concepts highlighted in the course. In one example of this teaching outcome, a learning assistant said,

> Actually understanding what you're coding and making sure you can tie it back to the physics. Like I said when you do the position update formula, you should be able to understand that that comes from this kinematic equation. You should understand how it relates and how it should affect it.

In this quote, the learning assistant describes what she wants her students to learning from the computational problems. She discusses that the students should be able to understand how particular lines of codes, like the position update formula, relate back to the physics equations they are familiar with in algebraic form. With this, she expresses that she wishes her students to gain an understanding of the *physics-code connection*.

In the *characteristic to moderate* theme, the *learning physics via computation focus* is characterized by a focus on the *impact of course design*. Moderating this characteristic means attending to the particularities of the way P Cubed is taught and incorporates computation, and seeking to minimize the negative impact of their limitations. Examples include the fact that students must share one laptop, that not all necessary information is always provided in the problem statements, and the availability of the four quadrants whiteboard for work organization. A learning assistant discussed this, saying,

> We have to consider who's taking over the group, like typing in by themselves, or maybe if somebody ... Like, if people have taken turns, but somebody hasn't typed in yet, then we do have to take into account that the code is something they should work on specifically, like working together with the code.

In this quote, she discusses the impact of students needing to share a single computer while solving the computational problems, which require code to be entered into the computer. She notes how individuals will sometimes dominate a group and do all the coding, and how other individuals may never get a turn to enter the code themselves, and how that dynamic is something learning assistants must monitor and address in their teaching on the computation days. Thus in this quote, she expresses that she moderates the *impact of course design* on computational days.

In the *teaching strategy* theme, the *learning physics via computation focus* is characterized by *leveraging the affordances of computational problems.* This refers to a learning assistant utilizing aspects unique to computation days in their teaching. An example of leveraging such an aspect is discussed by a learning assistant who said,

> I'll be like, "it's acting this way, why is it acting that way?" And when the students realize that, that's not possible, I'll start questioning things that they're missing. And if they see what they're missing, then they try to add that into the problem. This, once again, goes into pseudo code, because if they see what they're missing, I usually tell them to write it out first, so that they don't make those errors.

In this quote, the learning assistant describes how he will encourage his students to write pseudocode when they encounter difficulties on computation days. By pseudocode, he is referring to an approximation of what the desired code is, not yet worrying about entirely correct syntax. He explains that he will have students write this almost-code out on their whiteboard when they are having trouble getting it to work in the computer. As pseudocode is an attempt at writing information in a way the computer will ultimately be able to understand, it is a construct uniquely relevant on computation days. In this way, this learning assistant discusses employing a teaching strategy which *leverages the affordances of the computational problems.*

Considering these four variations together, there is a coherent approach to teaching computational problems that emerges that is centered around a focus on computation as a means of learning physics. With this emphasis on computational problems as a pedagogical tool, it is consistent that a learning assistant would view the utility of computation to be its ability to aid students' content learning. It also follows that a learning assistant with this approach would employ teaching strategies which leverage the capabilities of computation, given that they focus on computational problems as a means for students to learn physics concepts. The desired teaching outcome in the *learning physics via computation focus* is an understanding of the physics-code connection, that is, an understanding of exactly how the computational work relates to the physics concepts being taught. It is unsurprising that a learning assistant with this approach would want their students to understand the physics-code connection, because they view the computational problems as fundamentally being a venue for students to learn the physics concepts. With that view, it is understandable that they would want their students to explicitly understand how the code and visualizations present in the computational problems are connected to the physics. Finally, the characteristic moderated in this approach is the impact of course design based. Because the *learning physics via computation focus* as a whole is very focused on computation as a pedagogical tool and is grounded in the context of education, it is consistent that a learning assistant with this approach would pay attention to the classroom in which they are teaching, particularly the limitations and affordances that it presents, resulting in a focus on moderating the impact of the course's design in their teaching. This combination of four variations together characterize an approach to teaching computational problems that focuses on students learning physics via computation.

Computation as a tool focus

The *computation as a tool focus* is an approach to teaching computational problems that emphasizes the usefulness of computation as a method of approaching problems. Computation is treated as a tool that is valuable in mathematical and scientific problem-solving.

In this *utility of computation* theme, the *computation as a tool focus* is characterized by the belief that *computation makes difficult problems easier*. It is a perception that computation provides affordances that are an important part of modeling or solving complex problems. One learning assistant expressing this belief said,

> What makes the computer good is that it involves ... Like a big thing is the time step. The smaller you make that time step, the more accurate everything is. If you wanted to write and draw that out, you could, but you'd have to use a grid system. You could. I don't know how much that would actually help or prove.

In this quote, the learning assistant discusses that computers can be used to carry out iterative numerical calculations, and that it is simple to control how many iterations the computer calculates by modifying the time step (the interval between each calculation). He contrasts that with how difficult it would be to do this analytically. He explicitly identifies the ability to do an increasing number of calculations easily as "what makes the computer good". By articulating and emphasizing how computation can be utilized to carry out difficult calculations, he indicates a belief that the utility of computation is that it *makes difficult problems easier*.

In the *teaching outcome* theme, the *computation as a tool focus* is characterized by an emphasis on students appreciating the *capabilities of computation*. With this outcome, a learning assistant wants their students to understand the benefits that computation provides.

This is closely tied to the aforementioned belief that the *utility of computation* is that it *makes difficult problems easier*. While computation *making difficult problems easier* describes what the learning assistant perceives the usefulness of computation to be, the *capabilities of computation* describes what they want their students to takeaway from their experience with computation. An example of this appears from a learning assistant who said,

> The computation is important, it's an important skill, but understanding how the computation is helping them solve physics is always what I think about the most. The computer is solving all these equations and updating all this stuff, so what does that mean on pen and paper, and what does that mean for the physics?

In this quote, the learning assistant discusses how she focuses on how computation helps students solve the physics problems. She explicitly states how this is the important part of computation, and how it is more important than just the skill of being able to program. She expresses that what she wants students to understand how exactly it is that the computer is helping them. In this way, she suggests that the desired teaching outcome she has for her students is that they gain an understanding of the *capabilities of computation*.

In the *characteristic to moderate* theme, the *computation as a tool focus* is characterized by *student attention to programming details*. This means an attention to preventing students from becoming too caught up in the details of syntax and coding, to the detriment of their understanding the larger picture of computation. One learning assistant moderating this characteristic said,

> When it's just a spacing error that they've been working on for ten minutes, that's not super productive. And hopefully they just call me over when that happens, but I'm sure there are times when they're just messing with an error for 15 minutes, or ... probably not that long. Hopefully not to that point, but

> where they still have no idea how to fix it, and it's not helping them learn the physics, and it's not really helping them learn coding, 'cause they're just trying to find this tiny error.

In this quote, the learning assistant describes a difficulty students often have during the computational problems: getting their code properly spaced and tabbed. She discusses how spending too much time on this sort of error is not a good use of the students' time, explicitly noting that it does not help them learn the physics concepts *or* coding. She also expresses that she hopes she is able to intervene before the students waste too much time on a task like this. By treating the navigation of this sort of error as not aligned with learning coding and by indicating that she does not want students to spend time on these types of issues, she indicates a desire for students to not focus on unimportant programming details to the neglect of other computational skills. In this way, she expresses that *student attention to programming details* is a characteristic she moderates.

In the *teaching strategy* theme, the *computation as a tool focus* is characterized by *encouraging reflection on coding*. This means prompting students to think more deeply about how their code functions and how they can best utilize the program. A learning assistant discussing this strategy said,

> I would get them to focus on talking about how the code is supposed to be iterative. It's supposed to do the calculations for you. You shouldn't be doing the calculations outside of it and inputting numbers because then you're constraining the code to specific parameters, [but] the code is very versatile. You're supposed to be able to just hit run, change things to see how changing the variables affects the system.

In this quote, the learning assistant discusses how he will encourage his students to talk about what the code is able to do, such as carrying out calculations and allowing one to keep parameters variable. He emphasizes that the code is "very versatile" and that this should be leveraged, and he describes how he encourages his students to discuss these matters. This focus indicates a teaching strategy that is based on *encouraging students to reflect on coding*.

These four variations considered at once illustrate a coherent approach to teaching computational problems that is based around a focus on computation as a tool. Given a focus on computation as a tool, it follows that this teaching approach is characterized by a belief that the utility of computation is its ability to make difficult problems easier when leveraged, as this represents an example of its application as a tool. It also follows that a learning assistant with this approach would want their students to understand the capabilities of computation that make it such an important tool. In order to achieve this desired teaching outcome, it is consistent that a teaching strategy focused on encouraging reflection on coding would be employed. Prompting such reflection would facilitate students developing an appreciation for the affordances that computation provides them, and this emphasis makes sense given a focus on computation as a tool. The characteristic to moderate in this approach is student attention to programming details, which is also consistent with a belief that computation is a valuable tool. A learning assistant with this approach perceives computation to be more than simply entering syntax, instead treating computation as an important tool that can be utilized in modeling and solving difficult problems. Correspondingly, they do not wish their students to become bogged down in the details of syntax and leave with the impression that that is all that computation is. Rather, they want students to gain an appreciation of the greater value of computation. In this way, these four variations come together to indicate an approach to teaching computational problems that is focused on computation as a tool.

Shifting perceptions of learning focus

The *shifting perceptions of learning focus* is characterized by an emphasis on computational problems as an opportunity to affect students' beliefs about and approaches to learning. Computation is viewed as more than a pedagogical or problem-solving tool, and is instead treated as a means to impact students' ongoing ideas about how they learn and approach problems.

In the *utility of computation* theme, the *shifting perceptions of learning focus* is characterized by the belief that *computation offers a space for broader skills to be developed.* These skills could include how to collaborate effectively, how to think in new ways, and how to persevere through challenging problems. One learning assistant with such a belief said,

> That's [the computation problems] definitely where I see them learn a lot of effective ways to work in a group or in a team, which that's a big part of this class. Going forward, they definitely will need to know how to do that.

In this quote, the learning assistant describes how she has observed that the computation days are where the students most learn how to collaborate. She goes on to state that this is an important skill for them to know beyond the course. With this, she indicates a belief that the computational problems' utility is their ability to *offer students a space to develop broader skills* that go beyond physics and computation.

In the *teaching outcome* theme, the *shifting perceptions of learning focus* is characterized by *a new approach to learning.* This refers to a desire for students to develop a new approach to their learning through the computational problems. A learning assistant with this goal for their teaching said,

> I was trying to get them to see that, "Okay, if these two conditions are conflicting, then that statement will never be true, so that segment of code will never run." [...] If it's high up, then that just stops the code. Trying to get them to think through it logically rather than just like, "Okay, well let's just type something in and see if that changes anything," so stepping back and going, "Okay, well we know that this is true, we know this, and let's just look at this from a logical physics perspective rather than a coding perspective."

In this quote, the learning assistant describes a situation in which her students' code was not running because they had entered conflicting conditions. She explains how she wanted her students to think "logically" through the code and error, rather than simply making changes arbitrarily, demonstrating a desire she had for her students to take a more intentional and methodical approach to their problem-solving. This sort of focus on changing how students approach their learning and problem-solving is indicative of a new approach to learning to being her intended teaching outcome.

In the *characteristic to moderate* theme, the *shifting perceptions of learning focus* is characterized by *student attitudes*. When moderating this characteristic, a learning assistant focuses on ensuring that students do not become too frustrated or unhappy while working on the computational problems. A learning assistant moderating this characteristic with her teaching said,

> If they say something like "this is so frustrating, like I just want to give up," then you'll see them kind of start to get disengaged I guess. Like while you're doing the trial and error, usually the whole group is kind of looking at what's going on and is involved and wants to fix it and make it work. When you see them start to sort of you know, fall back and give up essentially then that's kind of where you want to make sure that you get them on the right track I guess.

In this quote, the learning assistant describes how she identifies when students have become frustrated to the point of no longer participating. She notes that at the beginning of problems, when groups are typically testing what different changes to the code do, students are generally engaged, but that as the problem progresses, frustration can lead to students becoming disengaged. She highlights that it is important to make sure that students do not get to that point of frustration. This focus on preventing students from becoming too demoralized indicates that she perceives *student attitudes* to be an important characteristic to moderate.

In the *teaching strategy* theme, the *shifting perceptions of learning focus* is characterized by *leveraging collaboration*. When employing this strategy, learning assistants capitalize on the fact that the course is a collaborative learning environment, and that students work in groups. One learning assistant discussing this teaching strategy said,

> I might say something like you know, ask somebody, ask a group what they are doing and if someone responds and it looks like the other two aren't paying any attention, I might ask, "Oh, are you guys good with that?" or like "Are you guys on the same page?" or "Do these guys understand that?" or something like that to sort of let them know that they should be conversing.

In this quote, the learning assistant describes how she will ask questions of a group that are targeted at assessing if there is agreement amongst the students and if all the students understand the group's work. She explains that she does this to convey to them that they should all be discussing the problem and concepts with each other as they work. This focus on encouraging students to take advantage of the fact that they are working in groups by having more discussions is an example of employing a teaching strategy that *leverages collaboration*.

In combination, these four variations describe an approach to teaching computational problems that is focused on computation as a way to shift students' perceptions of learning. With this view of computation in mind, it follows that the desired outcome of a learning assistant's teaching would be for students to adopt a new approach to their learning from the avenue for this that computation provides. It also is consistent that a learning assistant focused on computation as a way to shift learning perceptions would believe the utility of computation to be that it provides a space for students to develop skills that are beyond content. Skills like collaboration and intentionality when problem-solving are tied to how students' approach and perceive their learning, and so a learning assistant with a focus on shifting perceptions of learning would emphasis computation's utility in developing those skills. The *shifting perceptions of learning focus* is characterized by a teaching strategy that leverages collaboration. This strategy is also aligned with this focus because by leveraging collaboration, a learning assistant utilizes an aspect of the learning environment that is specifically designed to alter how students approach their learning and problem-solving. This strategy thus implicitly addresses how students approach their learning, and continues the focus on computation as a way to shift perceptions of learning. The characteristic to moderate corresponding to this approach is student attitudes. In order to attempt to shift students' perceptions of learning through the computational problems, it is unsurprising that a learning assistant would attend to student attitudes, and in particular, make sure students did not become frustrated to the point of disengagement. If a learning assistant is focused on shifting students' perceptions of learning, it is understandable that they would believe that engagement and a positive attitude are necessities to being able to influence students in this way. Thus these four variations when considered together comprise an approach to teaching computational problems that focuses on their ability to shift students' perceptions of learning.

Confirming final categories of description

Having defined and articulated the reasoning behind the categories of description in Table A.13, the final step in analysis was to review the remaining preliminary themes in Table A.1 and confirm that they were accounted for within the final four themes, or that they could justifiably be neglected.

Several preliminary themes were already accounted for within the final themes upon closer analysis. It became evident that some preliminary themes had emerged based on characteristics that were superficial in light of the deeper themes and categories that had developed. In specific, the *written feedback*, *varying levels of student programming experience*, *acceptable places to end computation days*,*minimally working programs*, *solution manuals*, and *teaching challenges* themes were largely already described by the final four themes in Table A.13. This is because many of the portions of transcript that had initially been sorted into these preliminary themes were simply context-specific discussions of learning assistants' teaching strategies. An example appears in the quote below,

> [Using minimally working programs] impacts my teaching a lot because I feel like I only really focus on the things I teach them how to code, like understand the code, or more like the while loops. I teach them about what's already there and it's not like I'm starting like this is what code is, and this is how you code things, like a coding class would teach you. And so you can focus specifically on while loops and if statements, which really limits the amount of coding you're necessarily teaching them and you can focus more on the physics side of it.

While this learning assistant discusses minimally working programs in this excerpt, he ultimately is discussing that he seeks to avoid programming becoming a distraction. He emphasizes how he teaches computational elements like while loops and if statements, but does not get into the details of programming "like a coding class would". In this way, he expresses an attention to ensuring that those details do not become the students' focus. Thus, this excerpt is accounted for within the *characteristic to moderate* theme, specifically the *student attention to programming details* variation. The majority of the transcript sorted into the aforementioned preliminary themes was similarly better captured by the final themes.

Other preliminary themes were eliminated because they were found to not be central to our phenomenon of interest: learning assistants' approaches to teaching computational problems. The *different student approaches to computation*, *differences in student behavior solving computation versus analytic problems*, *what students should do when solving computation problems*, *why code in groups*, and *student challenges* themes were neglected because upon closer analysis, it was observed that while they did relate to learning assistants' perceptions of the computational problems, they did not provide insight into their approaches to teaching. In the *student challenges*, *different student approaches to computation*, and *differences in student behavior solving computation versus analytic problems* themes, learning assistants simply shared their observations of students, but did not connect these observations to their teaching. In the *why code in groups* theme (and the portions of the *written feedback*, *varying levels of student programming experience*, *minimally working programs*, and *solution manuals* themes that were not already accounted for by the final themes), learning assistants shared their opinions on the design of P Cubed, but again, did not connect these opinions to their teaching and did not elaborate sufficiently for their comments to give insight into their approach to teaching. In the *what students should do when solving computation problems* theme, learning assistants discussed the ideal problem-solving approach to computational problems, but did not describe why they held that belief or how it impacted their teaching. In all of these cases, interesting information about the learning assistants' perceptions of computational problems was revealed, but this information was not productive in describing their teaching approach.

For example, in the *student challenges* theme, one learning assistant discussed a problem that requires the students to model the motion of a rotating disk, in which the given code defines the y-axis to be the axis of rotation. She notes that this causes confusion for the students, because in analytic problems, the z-axis is often taken to be the axis of rotation.

> I think, I mean like, I feel like they are going to get confused about anything new, but that one, I know there was a lot of confusion with the different things. There was an axis and the origin, and so I know I had discussions with both my groups about what those meant and think it's also confusing because it's like in the z-axis, but I think on the code it's on the y-axis, something like that. So, I don't know, all of those changes, kinda I think make those a little bit difficult to understand.

The learning assistant's discussion of how students struggle with coordinate systems in the computational problems gives some insight into her opinions on computational problems and the students, but it does not give insight into how she approaches her teaching overall. While she does state that she "had discussions" with her groups about this particular issue, it doesn't reveal her *teaching strategy* or *teaching outcome*, and it doesn't give information that is helpful in identifying the variations in learning assistants' teaching approaches.

Having thus confirmed that the final themes and categories in Table A.13 were sufficient to meaningfully describe the learning assistants' experiences as they related to their teaching approaches, analysis was concluded.

Validation

In addition to the processes described in this appendix, the results were subject to validation throughout analysis and upon completion. The entire analysis process was conducted in regular consultation with a researcher with expertise in phenomenography. All analysis decisions were subject to scrutiny and discussion, and had to be adequately justified through evidence from the transcript and defensible arguments. This included decisions to merge themes or variations, eliminate themes or variations, and especially decisions on the final groupings of variations defining each category of description. In addition to this on-going validation, at several intermediate points in analysis, preliminary results were presented to external groups for critique and feedback. Finally, upon the conclusion of analysis, the final results, the interview transcripts, and examples of coded transcript were provided to another researcher for external validation of the results. Based on the evidence and arguments provided throughout this appendix and the validation of these external researchers, we argue that the results presented here constitute a novel and legitimate phenomenographic result that gives meaningful and useful insight into learning assistants' approaches to teaching computational problems.

Appendix B

Sample computational problem

The following appendix provides an example of a computational problem that is taught in the course in which the study presented in Chapter 3 took place. In the class session before the students solve the problem here, they solve analytically for the radius and speed of geostationary orbit. This problem requests that they now model their solution computationally. The problem statement, the VPython code students are provided, and an example of correctly modified code are presented here.

Problem statement

Carver is impressed with your work, but remains unconvinced by your predictions. He has asked you to write a simulation that models the orbit of the satellite. To truly convince Carver, the simulation should include representations of the net force acting on the spacecraft, which has a mass of 15 x 10^3 kg. Your simulation should be generalized enough to model other types of orbits including elliptical ones.

Given code

```
from __future__ import division
from visual import *
from visual.graph import *
from physutil import *

#Window setup
scene.range=7e7
scene.width = 1024
scene.height = 760

#Objects
Earth = sphere(pos=vector(0,0,0), radius=6.4e6, material=materials.
    BlueMarble)
Satellite = sphere(pos=vector(7*Earth.radius, 0,0), radius=1e6, color=
    color.red, make_trail=True)

#Parameters and Initial Conditions
mSatellite = 1
pSatellite = vector(0,5000,0)

#Time and time step
t = 0
tf = 60*60*24
dt = 1

#MotionMap/Graph
SatelliteMotionMap = MotionMap(Satellite, tf, 20, markerScale=2000,
    labelMarkerOrder=False)

#Calculation Loop
while t < tf:
        rate(10000)

        Fnet = vector(0,0,0)

        pSatellite = pSatellite + Fnet*dt
        Satellite.pos = Satellite.pos + (pSatellite/mSatellite)*dt

        SatelliteMotionMap.update(t, pSatellite/mSatellite)

        t = t + dt

        #Earth Rotation (IGNORE)
        theta = 7.29e-5*dt
```

```
        Earth.rotate(angle=theta, axis=vector(0,0,1), origin=Earth.pos)
```

Example of correctly modified code

```
from __future__ import division
from visual import *
from visual.graph import *
from physutil import *

#Window setup
scene.range = 7e7
scene.width = 1024
scene.height = 760

#Objects
Earth = sphere(pos=vector(0,0,0), radius=6.4e6, material=materials.
   BlueMarble)
Satellite = sphere(pos=vector(4.2e7, 0,0), radius=1e6, color=color.red,
     make_trail=True)

#Parameters and Initial Conditions
mSatellite = 15e3
pSatellite = mSatellite*vector(0,3073,0)

G = 6.67e-11
mEarth = 5.97e24

#Time and time step
t = 0
tf = 60*60*24
dt = 1

#MotionMap/Graph
SatelliteMotionMap = MotionMap(Satellite, tf, 20, markerScale=2000,
   labelMarkerOrder=False)
FnetMotionMap = MotionMap(Satellite, tf, 20, markerScale=2000,
   labelMarkerOrder=False)
separationGraph = PhysGraph(numPlots=1)

#Calculation Loop
while t < tf:
        rate(10000)

        Fgrav = -G*mSatellite*mEarth*Satellite.pos/(mag(Satellite.pos)
           **3)
```

```
Fnet = Fgrav

pSatellite = pSatellite + Fnet*dt
Satellite.pos = Satellite.pos + (pSatellite/mSatellite)*dt

SatelliteMotionMap.update(t, pSatellite/mSatellite)
FnetMotionMap.update(t, Fnet)

separationGraph.plot(t,mag(Satellite.pos))

t = t + dt

#Earth Rotation (IGNORE)
theta = 7.29e-5*dt
Earth.rotate(angle=theta, axis=vector(0,0,1), origin=Earth.pos)
```

Appendix C

Interview protocol

The following appendix presents the protocol used for the interviews carried out for the study presented in Chapter 3. As described in Chapter 3, the protocol does not represent a strict order of required questions. Instead, it served as a guide for the interviewer to ensure that as complete a description as possible of the participants' experiences was obtained.

Background

- What is it like to teach in P-Cubed?
- How long have you been teaching in P-Cubed?
- Did you have any teaching experience prior to P-Cubed? Could you describe it for me?
- Have you had any other teaching experiences since beginning in p-cubed? Can you describe them for me?
- What sort of computational experiences did you have before P Cubed?
- Since teaching in P Cubed have you gained any further computational experiences?

P Cubed context

- Describe what computation looks like in P-Cubed.
- Describe what a typical computational problem looks like.
  - Can you talk about a specific problem?
  - What kinds of tasks are students asked to do?
- What is a model? What is modeling?

- Is there a difference between models on analytic days and models on computation days?
- Why do you think the computational problems are designed the way they are?
- What do you think of using VPython?
  - How does it impact your teaching?
- What do you think of minimally working programs?
  - How do they impact your teaching?
- Why do you think we pick the topics we do for the computational problems?
- Are there any differences among the computational problems?
- What are the learning goals for students are on computation days?
- We give the students some other tools to use, such as the four quadrants and written feedback. Can you describe your experience with those?
  - Why do you think we have them?
  - How did you use them in your teaching?
- Why do we have students work in groups? Why do computation in groups?
- Why do we have 15 instructors in the room?
- At the beginning of the semester, we have you go through some training about being an LA. Can you tell me your experience of it?
  - How did it affect your teaching?
  - What do you think the instructors' goals for your teaching are?
- During the semester, we have pre-class and post-class meetings every week. What was your experience of those?
  - Why do you think we have them?
  - How did they affect your teaching?
  - Do you do anything else to prepare for teaching?
- We give you solutions including tutor questions. Can you tell me your experience with them?
  - What do you think their purpose is?
  - How do you use them?

Teaching in P Cubed

- Moving into the classroom specifically, can you describe your teaching on a computational week, starting with Tuesday and then moving onto Thursday?
- Are there specific things you do and say? Why?
- Are there specific student actions/comments you watch out for?
  - What do you do when you see them happen?
- Are there things you avoid doing? Why?
- How do you decide when to go talk to a group?
- How do you decide when to give information versus give hints versus ask questions?
  - Is it affected by the issue being a syntax error versus a conceptual misunderstanding versus something else?
- What kinds of questions do you ask? Why?
- How do you decide whom to ask questions to?
- Where do you want a group to be after you interact with them?
- Do you see groups take different approaches to computational problems?
  - How do you deal with those approaches?
- Students often struggle with the geostationary orbit problem. Can you describe what you've experienced and how you handle it?
- What do the students struggle with on computation days?
  - Why do you think this is challenging for them?
  - How do you help students resolve the issues you've mentioned?
  - Do you think students learn from these situations?
  - How do you decide when struggling or frustration is okay?
- How does teaching different students affect your teaching? Different groups?
- How do you balance having two groups?
- Do you change how you work with a given group over time?
- What do you see as your role as a teacher in P Cubed?
- What is your role on the teaching team?

General thoughts on teaching

- How would you describe your general approach to teaching?
  - ☐ How did you develop that approach?
  - ☐ How does that apply to computational problems?
- When do you know you have done a good job as a teacher?
  - ☐ What kind of progress do you look for?
- When do you know that your students have learned something?
- What does understanding mean?
  - ☐ What shows a student has it?
- What's the most important thing for students to do in class to learn?
  - ☐ How does that thing lead to understanding?
  - ☐ How do you make sure students do that thing?
- Is it important for students to like you? Why?
- By the end of the semester, what is your goal for the students you work with?
- Why did you want to be an LA?
- Why do you think you were chosen to be an LA?
- What do you think you personally bring to the classroom as a teacher?

Closing Question

- Is there anything you'd change about the way P Cubed uses computational problems?

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