ABSTRACT

Title of dissertation: BECOMING A PHYSICIST:
HOW IDENTITIES AND PRACTICES
SHAPE PHYSICS TRAJECTORIES

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This dissertation studies the relationships and processes which shape students' participation within the discipline of physics. Studying this early disciplinary participation gives insight to how students are supported in or pushed out of physics, which is an important step in cultivating a diverse set of physics students. This research occurs within two learning environments that we co-developed: a physics camp for high school girls and a seminar for undergraduate physics majors to get started in physics research. Using situated learning theory, we conceptualized physics learning to be intertwined with participation in physics practices and identity development. This theoretical perspective draws our attention to relationships between students and the physics community. Specifically, we study how students come to engage in the practices of the community and who they are within the physics community. We find that students' interactions with faculty and peers impacts the extent to which students engage in authentic physics practices. These interactions also impact the extent to which students develop identities as physicists. We present implications of these findings for the design of physics learning spaces. Understanding this process of how students become members of the physics community will provide valuable insights into fostering a diverse set of successful trajectories in physics.

BECOMING A PHYSICIST: HOW IDENTITIES AND PRACTICES SHAPE PHYSICS TRAJECTORIES

by

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Foreword

The three body chapters of this dissertation are in various stages of publication. These chapters were written in collaboration with members of the dissertation committee.

Chapter 3 has been submitted to *Journal of the Learning Sciences* and is included here verbatim. This paper was co-authored with Professor Ayush Gupta. Chapter 4 has been submitted to *Physical Review* - *Physics Education Research* and is included here verbatim. This paper was co-authored by Professor Chandra Turpen and Professor Andrew Elby. Chapter 5 is written in collaboration with Professor Andrew Elby and Professor Chandra Turpen and will be prepared for publication.

In each case, the format of the work included has been altered to conform with standard dissertation format. The dissertation examining committee has determined that Gina Quan has made substantial contributions to the jointly authored work warranting its inclusion in the dissertation.

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Chapter 1: Introduction

Physics is doing a poor job recruiting and retaining women and underrepresented minorities [1]. At the undergraduate level, women receive 20% of bachelors degrees in physics, whereas African American, Latino, and Native American students receive less than 10% of bachelors degrees physics [2]. These percentages are far less than the fraction of the population comprised by each group. For women, representation has stagnated, and for African American students, representation has declined in recent years [2].

Common ways of discussing STEM retention fail to account for the complexity of students' experiences. For example, the "pipeline metaphor" models physics retention as a stream of students flowing through a physics pipeline until they "leak" out (leaving physics) or arrive at a fixed endpoint (where they are full-fledged physicists). Such metaphors often lead researchers to identify (and attempt to plug) leaky points along the pipeline, and correlate leaks to demographic categories such as race, gender, and socioeconomic status. Overall, this metaphor tends to assume that students are a homogeneous fluid, and the processes by which students become physicists is a single, linear pathway [3].

One limitation of the pipeline metaphor is that it obscures aspects of STEM culture and practices that disproportionately marginalize students from diverse backgrounds [3, 4]. Prior research has documented how harsh practices and the unwelcoming culture of STEM disciplines contribute to attrition [5–7]. These features of STEM culture disproportionately impact women and students of color, even those who are successful at coursework [5,8]. Moreover, the singular pathway of the pipeline, as well as the homogeneity of students flowing through the pipeline, is assimilationist. It does not account for the diversity of students' backgrounds into physics and it assumes that the process of "becoming" a physicist looks the same for all students [9]. It is important to move beyond the "pipeline" metaphor of retention and instead consider how to foster a diversity of successful STEM pathways [10].

Within my dissertation, my work studies the cultural aspects of the physics community that contribute to how students are supported within or pushed out of physics. An understanding of these processes is necessary in order to foster a diversity of pathways into STEM.

My dissertation research aims to understand the relationships and processes that support participation in physics. I take an interventionist approach to my work. I designed innovative learning spaces and conducted research on how students experience physics in those spaces. These aspects of my work—research and practice—bear on each other. Research-based instructional strategies supported my course design, and my experience as an instructor informed my research on those settings. Several values underlie my interventionist approach: 1) Increasing equity in physics, 2) engaging in authentic disciplinary physics experiences, and 3) creating *entry points*, or opportunities that open up new possibilities for future participation in physics. My dissertation work occurred in two settings: a physics summer camp for high school girls and seminar for undergraduate physics majors participating in research experiences.

In the next few sections, I situate this research in my personal history and the context in which it occurred. First, I describe a transformational learning experience in the Compass Project and how it led to my focus on authentic physics experiences and attending to identity and participation. Next, I situate my focus on equity within the current political context. I conclude this chapter by summarizing research results from the three body chapters in this dissertation.

1.1 Experiencing authentic science in a supportive community

In this section, I present a vignette of my experience as an undergraduate physics major in the Compass Project at the University of California, Berkeley. The purpose of this vignette is to motivate attention to scientific practices, community building, and identity development in physics classrooms.

The summer before my freshman year at the University of California, Berkeley, I participated in a summer program run by the Compass Project. The intent of the summer program was to support the success of underrepresented students in the physical sciences. Core principles of Compass included developing a supportive community, fostering student agency, and working on challenging, interesting physics problems together.

The two weeks I spent in Compass centered around the question *"what is time?"* Digging deep into this question, we explored a good portion of special relativity, including grappling with the concepts and learning the basics of Lorentz transformations. These classes were unlike any classes I had ever taken in high school. We developed experiments and physical models to test our ideas. What we did each day was determined by own curiosities and questions as students. We did science as a classroom community, sharing our ideas and celebrating one another's contributions.

I remember one moment when we were learning about length contraction and time dilation. My tablemate, still eating a banana from breakfast, exclaimed, "Hold on! So you're telling me that if I threw this banana fast enough, I could eat it in one bite?" Someone else chimed in, "but wouldn't your mouth seem smaller from the banana's point of view?" This seemed like a contradiction worth resolving, so our instructors switched gears and we spent the day exploring the conundrum. With a great deal of productive frustration and instructor scaffolding, we eventually resolved what I later came to know of as the Pole and Barn paradox.

Getting to be an active participant in student-centered scientific inquiry has fundamentally impacted what I value as an instructor and researcher. And while I didn't have the language at the time to articulate the reasons why my experience in Compass was so meaningful, there are some features that I now see as consequential:

We engaged in scientific practices for the purpose of generating knowledge about complex physical phenomena. Learning in Compass meant engaging in scientific practices that were missing from our typical undergraduate courses. We designed and implemented our own scientific investigations and refined models of physical phenomena [11]. Aligned with principles of constructivism [12], it was up to us to generate knowledge. We had agency over judging and evaluating ideas [13] and constructed scientific arguments [14, 15]. There was also the sense that we were building scientific claims for ourselves rather than confirming a known result. I see this as aligned with Engestrom's notion of *expansive learning*, which treats learning as the "transformation and creation of culture... and on the formation of theoretical concepts" [16]. As students, we did not see ourselves as receiving transmitted information, but instead saw ourselves as generating models of the physical world.

Doing science together meant participating in a Compass community. Compass explicitly valued collaboration as an important aspect of doing science [17, 18]. The classroom design supported productive collaboration by letting us generate and work on open-ended, challenging problems where diverse sets of expertise were valuable [13, 17]. Our classroom community was characterized by shared norms that required us to listen to one another and resolve confusions and disagreements [17, 19].

Compass supported equitable access to physics identities. Compass norms explicitly supported equity by disrupting typical notions of what it meant to be "good" at science. It is common in other science classrooms that the students who are recognized as "smart" are the ones who have strong background knowledge and use excessive jargon. In those classrooms, only a limited set of students have access to positive science identities, meaning, only a limited few can be seen as "smart." Instead, Compass worked toward a classroom community that had an ethos of "learning together," where all students could meaningfully engage in collaboratively building physics knowledge. Compass implemented several classroom structures that reduced classroom hierarchy and supported opportunities for all students to develop positive physics identities.

Through Compass, I came to value science classrooms that supported authentic engagement in scientific practices, collaboration within a supportive community, and supporting students' identity development within physics. I see equitable learning in physics education attending to all of these aspects simultaneously. My belief that these kinds of classrooms are worth designing for and worth understanding motivates the work in this dissertation.

My driving research questions are:

> *What does it look like for students to participate in disciplinary practices?*
> and
> *How does engagement in these practices contribute to students' identity development and equitable access to physics participation?*

1.2 Recent attention to supporting equity and inclusiveness in the physics community

Supporting equity in physics has been an ongoing goal of many physicists in the professional physics community. Both the American Association of Physics Teachers and the American Physical Society have long-term committees focused on gender and racial diversity. The National Society of Black Physicists (NSPB) and National Society of Hispanic Physicists (NSHP) have existed for decades. In this section, I describe some recent inclusiveness efforts within the professional physics community. I motivate my focus on equity within these efforts because, as Tracy argues, research topics often become worthy of study due to their timeliness in a political or social climate [20]. Moreover, consideration of broader societal issues adds what Johnson calls *consequential validity*, the ability for research to have impact on science teaching practice in ways that align with a researcher's values [21]. As a person committed to social justice, my work *gains consequential* validity through informing the design of more inclusive physics spaces.

In the past two years, professional physics societies have voiced public statements affirming their commitment to inclusiveness in response to broader political events. Due to the increase in discriminatory legislation and executive orders, as well as unusually high instances of hate crimes stemming from the 2016 election [22], professional physics societies have revoiced their commitment to inclusiveness [23, 24]. In the 2016 Supreme Court case about affirmative action, *Fischer vs. Texas*, APS and AAPT both wrote public responses affirming the value of black students in physics classrooms [25, 26].

Professional physics organizations have also taken steps to toward making professional meetings more inclusive. Both APS and AAPT have adopted Codes of Conduct for professional meetings in the past year. In 2016, the APS Division of Atomic, Molecular, and Optical Physics (DAMOP) moved their conference in North Carolina as a result of anti-transgender bathroom bill, HB2. This effort was led by Steve Rolston, chair of DAMOP and the University of Maryland Physics Department. He noted, "The recently adopted Code of Conduct of the APS reinforces that we are inclusive society of scientists, and should all be treated with respect" [27].

Understanding sources of inequity and strategies to support inclusiveness has also impacted scholarship in physics education research. Recent special issues in physics education research journals include *The Physics Teacher*'s focused collection on race [28] and *Physical Review– Physics Education Research*'s focused collection in gender [29]. These examples illustrate the physics education research community's engagement in discussions of equity as they pertain to our lives and research.

1.2.1 How STEM disciplines are sites of marginalization

STEM communities are not only affected by what is happening in broader society, they are also sites in which marginalization occurs. Prior research has documented how this emerges in interactions, is embedded within departmental cultures, and stems from the historical formation of STEM disciplines.

At the interactional level, research has shown that women and students of color often face stereotypes and discrimination, such as being excluded from study groups and experiencing discriminatory remarks [30, 31]. Physics students from nondominant backgrounds also experience frequent microaggressions, subtle discriminatory exchanges toward someone based on gender, race, class, LGBT+ status, and other aspects of their identity [32].

Other work has shown how university and classroom cultures contribute to the marginalization of students. In Tonso's [33, 34] study of an engineering university, men were recognized as academically successful, whereas women who were competent at engineering were not recognized for their contributions. Work by Secules in an introductory programming class describes how the instructor's public affirmation of advanced questions and the high visibility of students' success on tasks led to a classroom hierarchy [35]. Despite being an introductory-level course, the cultural features marginalized students without programming backgrounds (who were often low socioeconomic status students, underrepresented minorities, and women).

From a historical perspective, STEM fields were largely formed by white men, and modern-day aspects of STEM culture tend to be aligned with the socialization of white men [36]. Seymour and Hewitt describe how undergraduate STEM departments tend to be competitive, and lack encouragement and collaboration [5]. They argue that these norms often feel unfamiliar to women, who are socialized to be collaborative and seek external validation. In other words, "treating women in the way understood by men" leads to isolation and attrition of women [5]. Other work has shown that in STEM fields, students from underrepresented backgrounds also do not know the "rules of the game," or the informal knowledge needed to succeed [37].

Understanding equity in STEM requires thinking about how marginalization occurs at several levels: within individual interactions, as emergent in local cultures, and as built in structurally in the discipline. Within this dissertation, I draw from these different perspectives to speak to equity.

1.3 Dissertation contexts: two non-traditional learning environments

The three studies of my dissertation occur in two learning environments, a summer camp for high school girls and a research seminar for undergraduate physics majors. Both of these learning environments are non-traditional physics spaces, meaning that they exist outside of the typical physics curriculum. I played a significant role in designing both of these learning environments in ways that were highly informed by my experiences in Compass. In both settings, students learn through project-based activities that support engagement in authentic practices. Explicit attention is made to the development of an inclusive disciplinary (pertaining to the physics discipline) community.

Summer Girls is a day-camp focusing on modern physics run by the Physics Department. I designed and implemented an interdisciplinary engineering design curriculum where students were given open-ended Arduino (robotics) design tasks and completed a final project. Two guiding principles supported the design of this course:

1. Developing a supportive classroom community where students saw each other as resources. Though students worked in pairs and trios each day, we encouraged students to go to each other for help.
2. Supporting student agency and freedom in the design process. Tasks were intentionally open-ended so that students could develop unique solutions to design problems and pursue creative ideas. For the final project, students were given the freedom to design any kind of final project they could think of using the Arduino, spare circuit parts, and anything they could scrounge up.

In one research thread that is not in my dissertation, I studied how different pairs of students learned to program together, and illustrate one case in which a student with programming experience facilitated her novice partner learning to program [38]. More details about the Summer Girls environment are discussed in Chapter 3.

The second learning environment was Physics 299B, an elective research seminar for undergraduate physics majors. This seminar pairs students with research mentors on physics and astronomy research projects. The development and research on this setting was funded by a collaborative grant between the University of Maryland and the University of California, Berkeley, which also studied physics community and identity in Compass. Two guiding principles impacted the design of Physics 299B:

1. Developing a supportive community which shares the ups and downs of doing physics research.
2. Giving students opportunities to reflect on and be proud of their work.

These principles led to much of the seminar consisting of small-group and whole-class discussions in which instructors facilitated reflection on students' research activities. More details about the Physics 299B environment are discussed in Chapters 4 and 5.

1.4 Structure of the dissertation

Tinkering, the use of ad-hoc trial and error toward solving a design problem, is a common activity in physics research. While tinkering has often been undervalued in design, chapter 3 illustrates the value of tinkering as a way to support students' engagement in design. This chapter paints a picture of what tinkering looks like at a moment-to-moment level, articulating the various steps of the tinkering process. I then consider how tinkering supported future learning. My analysis contributes to debate in engineering education on whether or not tinkering is a productive activity. I argue that tinkering can be productive toward some instructor and student goals and unproductive toward other goals; how one judges the productiveness of tinkering depends on one's goals. Though I situate my research on tinkering within the design and engineering education literature, I do see tinkering as a relevant activity to physics. Physics experiments and computational models often require design, and tinkering is an activity that is likely to emerge in doing physics research.

This work contributes to discussions on equity by questioning whether and why we might value the practice of tinkering. As prior research has shown, students have differential access to the valued practices of STEM classrooms, which has often led to the marginalization of students from underrepresented backgrounds. For example, Turkle and Papert [39] suggest that flexible, improvised approaches to design come more naturally to some students, but these approaches are undervalued. In contrast, abstract planning is more typically valued as a good design practice. Turkle and Papert found that women were more likely to use improvised approaches compared to men, and argued that only valuing abstract approaches marginalizes women. They advocate for *epistemological pluralism*, valuing multiple kinds of approaches to design. Similarly, my tinkering work critically examines what we value and recognize as "good" in classrooms and argues that we should develop good justifications of why we value some activity over others. I also draw attention to student activity that is typically not recognized as "good," and consider how that activity may be productive toward some goals. Questioning valued STEM practices and considering how those values may exclude students is important toward making our classrooms more inclusive.

Chapters 4 and 5 illustrate aspects of physics cultural norms which lead to students becoming part of (or kept at the periphery of) physics community within undergraduate research experiences. In Chapter 4, I analyze how the working environment and relationships between students and mentors can lead to students learning the "big-picture" aspects of how scientific practices fit together and how they serve a scientific purpose. By practices, I mean regular activities that physicists engage in toward the purpose of understanding the physical world (e.g. developing a model, analyzing data) [40]. I use Lave and Wenger's [41] *community of practice* framework, in which learning is seen as the process of shifting one's membership in the physics community. My analysis provides a framework for thinking about what authentic engagement in physics looks like and illustrates how engagement is impacted by the setting and structure of research activities.

Within my analysis, I conceptualize authentic engagement in physics practices to be whether scientific activities are connected to one another and embedded within a scientific purpose. I identify variations in how students participate in the physics community of practice as evidenced by differences in their senses of *connectedness* and *purposefulness* of scientific activities. I conceptualize *joint work* as the structure of the research project and the nature of interactions between students and mentors.

My central finding is that joint work between students and mentors impacts students' engagement in these scientific activities. In one case study, a student who had sparse meetings with her research mentor was unable to develop an understanding of connectedness and purposefulness of her work. In contrast, mentors who made themselves more available to students facilitated deeper understanding of purposefulness and connectedness.

This chapter speaks to equity by illustrating how different forms of joint work can open up or limit access to connectedness and purposefulness of scientific activities. Within the data, we saw differences in the degree to which students sought an understanding of connectedness and purposefulness. Depending on the degree to which students were supported in their engagement in connectedness and purposefulness, this could likely impact students' long-term trajectories. Additionally, this work illuminates how different forms of mentoring behaviors, such as leaving the burden on students to schedule communications, may hurt students with less familiarity and aggressiveness toward faculty (e.g. students from low socioeconomic backgrounds and first-generation college students).

Finally, Chapter 5 describes how features of sexism and classism are embodied within what it means to be a physicist in different physics spaces. This chapter zooms in on one case study, Cassandra, to understand shifts in her *personal identity* and shifts in what she perceived to be the *normative identities* of the discipline. *Normative identities* refers to the accepted and valued roles of physics students [42]. In Cassandra's experience, these normative identities carried implications for gender and socioeconomic status. For example, Cassandra reported that she commonly had to deal with unwanted objectification from male students. I illustrate how Cassandra's *personal identity* shifted in tandem with her perception of normative physics identities in ways that led to greater alignment between the two. This study revealed that having opportunities to meet her research mentor and other physics majors were consequential to these identity shifts.

This chapter speaks to equity by illustrating how patriarchy and classism make their way into Cassandra's life. In Cassandra's research experience and experiences in peer settings these dynamics were sometimes maintained. Other settings afforded opportunities for resisting these forces. An understanding of how individual students contend with power structures can help us develop a greater understanding of the ways in which these power structures function in students' everyday lives.

Chapter 2: Theoretical Perspective

In this chapter, I describe the sociocultural and cognitivist traditions from which I draw to conceptualize learning in Chapters 4 and 5. First, I briefly compare cognitivist approaches and sociocultural approaches to studying learning. I then describe the concept of a *community of practice*, as defined by Lave and Wenger, and what learning means within a community of practice. I elaborate on how I am using the term *identity* in this dissertation. Finally, I describe the epistemic approach underlying ethnographic methods, and how they apply to my work. The perspectives I present in this chapter apply to Chapters 4 and 5. I further elaborate on my theoretical perspectives in each of the body chapters of this dissertation.

2.1 Drawing from situated and cognitivist approaches

Cognitivist and sociocultural perspectives are two complementary research traditions in science education. While there are variations in cognitivist approaches to understanding learning, they tend to study learning with a focus on the individual student, with the goal of making the student more expert-like. Learning is broadly seen as the process of building more complex and refined cognitive structures and being able to complete more challenging tasks [12]. This involves the development of more expert-like conceptual understanding [43, 44], problem-solving skills [44], metacognitive skills [45], and epistemological stances [46].

Work stemming from this tradition aims to model students' cognition and conceptual change. One such model includes the perspective that students have incorrect ideas that are to be confronted by instruction [43, 44]. Another model of cognition is that students hold many conceptual resources that become activated in contexts [47,48] and the activation of these ideas need to be refined [49]. Cognitivist approaches have led to the development of curricula which support students' deeper understanding of conceptual knowledge through guided inquiry, and opportunities to construct new understandings (e.g. [50]).

Sociocultural perspectives characterize learning as a social process in which knowledge is situated within a setting or community. This perspective foregrounds the social interactions and routines of a community in which science is done [51]. Learning is a process that results in being able to participate in more complicated tasks within the disciplinary community.

Rather than designing classrooms with a focus on the construction of knowledge, a sociocultural approach emphasizes engaging students in authentic scientific practices (e.g. generating questions, constructing hypotheses, engaging in argumentation) [52]. While cognitivist perspectives may value authentic practices as a vehicle for learning science, sociocultural perspectives see practices as a necessary component of learning science. This emphasis on understanding how students engage in disciplinary practices motivates my *in situ* analysis of the design practice of tinkering in Chapter 3. Sociocultural perspectives conceptualize "learning science" to be more than just the development of knowledge or skills, but to also include participating in the activities, discourses [51], and relationships of the scientific community. In Chapter 4, I study how social interactions support and limit students' engagement in scientific practices and relationship-building.

Part of my motivation for taking a sociocultural approach is that science itself is done by people in a socially organized community. While science is often seen as the objective, cultureless, and unbiased discovery of knowledge, this is untrue. Social and anthropological studies of science reveal that science has cultural norms, rituals, and social processes that are part of how knowledge is constructed and evaluated [36, 53–55]. Science is also done by people whose beliefs and expectations influence what they choose to investigate and how they go about investigations [56, 57]. Thus, "doing science" is more than just the process of building claims about the physical world, it also involves becoming a part of the disciplinary community and learning the norms and practices of this community.

Seeing science as a culture laden with values and beliefs also complicates the process of learning science. In addition to learning being a process of developing more sophisticated understandings of phenomena, socioculturalists also view learning as the process of being enculturated into the beliefs and values of a scientific community. This enculturation can become especially challenging as students often have beliefs and values which conflict with those of science. As Lemke poignantly states:

> "We should give students opportunities to change their minds, but we should not do so unaware that we are thereby inviting them to join a particular subculture and its system of beliefs and values. We must also stop and consider whether we are, perhaps unnecessarily, making the price of admission to science the rejection of other essential components of students' identities and values, the bonds that link them to other communities and cultures. We cannot afford to continue to believe that our doors are wide open, that admission is equally free to all, that the only price we ask is hard work and logical thinking."

Sociocultural analyses show that the cultural and social aspects of doing science can sit in tension with students' personal histories. In Chapter 5, I model these tensions that are present in students experiences, and how they impact becoming part of the scientific community. In the next section, I describe how I am conceptualizing the physics community, and introduce the concept of a community of practice.

2.2 Communities of Practice

In this section, I describe the sociocultural framework, *communities of practice*. A *community of practice* is a set of people who work together on shared activities toward a set of shared goals. Wenger defines the community by three components, *mutual engagement* (the collaborative nature of relationships), *joint enterprise* (shared goals of the community), and *shared repertoires* (set of shared resources used toward the joint enterprise) [41,58]. Within a community of practice, *legitimate peripheral participation* (LPP) refers to the process of novices learning through engaging in joint work with experts [59]. Depending on the form and structure of these activities, they can facilitate deeper understanding of the community and engagement in more complex activities of the community.

Membership within the community is varied and there are a diversity of ways to participate. As Lemke [51] describes, the science community is an "organization of heterogeneity." Consider the physics research community, for example. There is a diversity of research areas within physics (e.g. atomic physics, astrophysics, physics education research). Professional physicists within the community also take on many roles (e.g. faculty, lab technicians, graduate students). All of these people can participate in different aspects of the joint enterprise of understanding the physical world (e.g. writing grants, bringing new people into the community through graduate admissions, organizing professional conferences). There are many functions that one's membership entails, but no member takes on all of these roles.

Learning and identity development are directly intertwined with shifting participation within the community of practice. The process of shifting participation is neither a linear, nor smooth process. Interactions with other members of the community can lead to participating in more central practices, or cordoning off access to central practices. Who one is and how one engages in disciplinary practices is dependent on the form and nature of the joint activities and interactions with others. Learning broadly entails being able to complete more complex tasks within the community, a deeper sense of the joint enterprise, and sense of how one's participation contributes to the joint enterprise [41].

This idea is similar to what Rogoff calls a "transformation of participation" [60]. Rather than seeing learning as merely a process of acquiring knowledge, or the process of being transmitted knowledge, Rogoff describes learning as changing one's participation in "shared endeavors." Within these endeavors, the roles are initially "asymmetric" between mature (experienced) and less mature members. The asymmetry refers to mature members leading activities that less mature members play a supporting role in. Through learning, the less mature members gradually take on more challenging roles and come to understand the practices of the community better.

Many researchers who draw on communities of practice use spatial metaphors to describe learning. For example, some describe learning as becoming a more central participant in a community [12,61,62]. Others describe learning as increasing intensity, centripetal movement [59], or "deeper" participation within a community. For two reasons, some researchers object to using spatial metaphors like "central" to describe learning. First, there are a diversity of ways that participation with respect to the community can shift. Even in being denied access to central practices of the community, one still learns more about the community and one's role within the community. Second, there is no true "center" of the community because the community is comprised of a diversity of roles. The community activities are multifaceted and not easily mapped onto a single dimension. Instead, these researchers argue that all learning is "shifts in participation." In this model, a student who is weeded out of an intro physics course and a student who begins to work more independently on a physics research project are both "learning," though what is learned, and the possibilities for future engagement differs between them.

I agree that there are a diversity of ways that one can be a full member of the community, and thus there is no true "center." But rather than seeing learning metaphors as *either* "becoming central" *or* "shifts in participation," this dissertation takes a *both–and* approach. I choose to conceptualize learning as process of moving from the periphery of the community toward more central and intense participation, with the understanding that the "center" reflects a variety of ways to participate. Using this "centrality" metaphor makes sense because I choose to study students becoming more (or less) aligned with professional physicists in their engagement in disciplinary practices and development of disciplinary identities. At the same time, my work pays attention to the multifaceted nature of the work and relationships in the community, and explicitly attends to these variegations.

2.3 Authentic practices

A communities of practice framework can be used to understand many kinds of communities. To understand the physics community specifically, it is important to first conceptualize the authentic physics practices within the physics community. I draw on literature from science education and philosophy of science to define physics practices.

I define scientific practices to be activities that are embedded within and are recognized as working toward the aims the scientific community [63, 64]. Practices are also logically coherent with respect to other practices (Berland et al. [65] refer to the set of practices as an "ensemble of activity.") I apply a framework from Ford [64] who draws on work by Rouse [66] to define authentic scientific practices from a holistic perspective. Ford argues that this practices perspective draws attention to how practices function in relation to one another and to the broader scientific enterprise [40]. He describes three key features of practices:

1. *Connectedness*: The performances of a practice interact with one another in a meaningful way, and that there is some way to judge the appropriateness of the performance.

2. *Purposefulness*: The performance is evaluated and critiqued within a purpose—within science, this purpose is its ability to "explain nature." (c.f. [65])

3. *Prospectiveness*: Practices are prospective or forward thinking, which captures how our scientific tools and approaches evolve over time.

The activity of running an experiment is considered a practice if the experiment is connected to a driving question about a phenomenon and to a sensible method of analyzing the data such that disciplinary knowledge could be developed. It would not be considered a practice if it was done as an isolated activity, independent of the underlying logic of how the experiment would produce scientific knowledge. Thus, the extent to which an activity is a practice is dependent on how it is embedded within the ensemble of activities and goals of the community.

2.4 Practice theory of identity

Now I present my conceptualization of identity in this dissertation. While there are a diversity of perspectives on identity, I use Holland's *practice theory of identity*, which draws from situated approaches toward learning [67]. In using a situated approach, identity is conceptualized broadly to be who one is within a community. As Gee describes, identity is being recognized as "a certain kind of person" within a context [68].

Within this dissertation, there are several components to how I understand identity. Identity includes both how one understands oneself, but also how one is recognized by others. These two aspects interact with one another; how one is seen by others impacts their understandings of themselves, whereas the ways that one sees oneself can impact the identities that others ascribe to them [3, 67, 69]. Holland emphasizes this dual nature of identity, which is "always, but never only 'in' the person, never entirely a matter of autobiography nor, on the other hand, entirely reducible to membership (voluntary or involuntary) in culturally, politically distinctive groups or social categories."

Identities are forged within a context, using the cultural resources of that setting to improvise one's identity [67]. Holland introduces the concept of *figured worlds*, a theory describing culture and identity. Figured worlds are the "sociohistoric, contrived interpretations or imaginations that mediate behavior and... inform participants' outlooks," meaning, the imagined cultures that individuals draw on to construct their identities. Work drawing on figured worlds has described how they are leveraged to create opportunities for asserting, shifting, and reconceptualizing identities [33, 70–73].

While I do not explicitly use figured worlds in my analyses, I align my work with conceptualizations of identity that integrate both recognition and participation. For example, Urrieta [72] defines *procedural identity* as how one participates in activities of the community, whereas *conceptual identity* refers to sense of who one is. Carlone and Johnson's framework for science identity is comprised of three components: recognition by others and oneself as being a scientist, performance of scientific activities, as well as knowledge and understanding of scientific content [31]. Similarly, Fields [74] divides identity into *self-narratives* (recognition by oneself), *other's narratives* (recognition by others), and *practice*. While these approaches divide up "identity" in slightly different ways, I draw from these approaches to hold both recognition and participation as components of identity.

Within the physics community, I conceptualize physics identity to have several interacting components: 1) how participants identify themselves with respect to physics (self-understandings) 2) how they are identified by others with respect to physics, and 3) how they participate in the physics community and activities of the physics community. This approach differs from more cognitivist approaches to identity, which tends to model individual's disciplinary identities as solely self-understandings that exist within individuals. Such approaches foreground internalized characteristics such as intrinsic motivation, interest, attitudes, and self-efficacy [75, 76]. And while these approaches do see interactions with others as playing a role in one's identity, they tend to include interactions to the extent that they bear on individuals internalized feelings of recognition (e.g. [75]). Looking at self-understandings using a situated lens recognizes that these self-understandings emerge within interactions with others within contexts, and requires modeling how self-understandings came to be through interactions with others.

To make this distinction more concrete, consider the experience of Savannah, a case study student in 299B. Savannah recounted an experience where she asked her research mentor if she could submit a poster abstract to a national conference. When her research mentor told her to also consider submitting a talk abstract, she described feeling more like a legitimate physicist. A cognitivist approach would model the student as having access to stories of recognition, which is correlated with greater physics identity. A sociocultural approach would also model how Savannah's physics identity came to be through interactions within the physics community. For example, Savannah was positioned as having expertise by her research mentor, and one could analyze the structures of the interaction patterns that allowed for this identity growth. Savannah was also invited into participating in a central physics activity (giving a talk); talks and poster presentations have symbolic value within the physics community, and the status associated with them supported Savannah's identity development. Using sociocultural lenses helps us build mechanistic models of how settings and activities contribute to identity development.

I recognize that identity development can also happen in many interactions that I don't have access to in interviews. It is plausible that students could choose not to share some interactions in interviews, or some interactions may not be as salient to students in the interview setting [77]. Other analytical approaches, such as analyses of observational data in multiple settings, would complement my work.

2.4.1 Identity trajectories

Identity trajectories focus on longitudinal changes in identity within a community [3,41,69]. Wenger outlines several forms of changes in identities: *inbound* (shifts toward more central participation), *outbound* (shifts toward less central participation, and toward central participation in new communities of practice), *peripheral* (consistently peripheral participation), *boundary* (participating in multiple communities as a broker between them), *insider* (consistent participation for members who have full participation) [41, 69]. Within this dissertation, I am most interested in what leads to trajectories becoming *inbound, outbound,* or *peripheral*, given that all focal research participants begin at the periphery. I am most interested in the possibilities for participation at a given point, and in particular, how experiences can open up or constrain such possibilities.

Holland and Leander describe how shifts in identities are in-part accomplished through *positioning* [78]. Positioning refers to descriptions of an individual in relation to a community (e.g. saying "she belongs in physics" positions her as belonging within the physics community). This also includes how individuals position themselves with respect to the community (e.g. "I am a physics person" positions me as a member of the physics community). Within a given interaction, social positions are "offered" and the person can accept or refuse the positions or parts of the positions [78, 79]. Accumulation of these identity-shaping experiences contribute to one's identity stabilizing over time. They refer to this process as *lamination*, how positioning moments occur and layer upon one another. These layers are heterogeneous and distinct and their presence leaves lasting impacts (e.g. feelings, artifacts) that can been seen in the individual.

2.5 Starting assumptions from ethnographic approaches

In this section, I describe the epistemic approach underlying ethnography. While ethnography is a methodology, the purpose of this section is not to describe the methods. Rather, this section describes the starting assumptions of these methods, and the theory underlying how these methods produce some knowledge about learning.

Ethnography is a methodology that has roots in anthropology and studies cultures with researchers embedded within those cultures. Ethnographies seek to build thick descriptions [80] of cultures, understand participants' meaning making, and identify patterns of behavior. While this approach was initially developed to understand non-western cultures, it has now been used in a variety of contexts, including in studies of undergraduate and professional STEM in the United States [5,7,34,36,81]. I now elaborate on several starting assumptions underpinning ethnography and how they pertain to the work in this dissertation.

Observing people in their environments— Ethnographies conduct *in situ* observations of participants in their natural environments. This is different from studying learning in a laboratory experiments, which is commonly done in psychological research (e.g. bringing participants into an interview room and asking them to solve physics problems). Observing people in their own environments is important because research done in laboratory experiments often has artificial features, and research subjects may frame the activities in unexpected ways [82]. As a result, psychological experiments have found that research subject's "lack" certain skills that anthropologists have been able to observe being performed by participants in *in situ* observations. In my own research, I observed students in both the Summer

Girls and Physics 299B settings. While the two Chapters on Physics 299B primarily rely on interviews, interview questions were developed based on ethnographic observations.

Coordinating insider interpretations with researcher observations—Ethnographies also rely on insider perspectives, interviews with members of the focal community about the community itself. These interviews complement the observations by providing insight to what an individual's experience is within the community, how participants perceive the goals and activities of the community, and what the "common sense" knowledge is within the community [36, 77]. Having multiple insider perspectives contributes to the ethnographer's understanding of the variation of roles and perspectives throughout the community.

Long-timescale engagement with a setting—Ethnographic methods tend to study participants over months or years. This extended engagement in the observed community is important toward building shared meaning between participants and ethnographers [77]. Members of communities have shared language and nuanced ways of understanding words and phrases that may feel familiar to outsiders in the community. For example, some physics education researchers use the phrase "mean field approximation" to refer to comparing a single student to the average of all other students in a course. This is a metaphor for a technique used in many-body physics where a complicated system of interacting particles is approximated by a single particle interacting within a mean field that is the statistical average of the other particles. Understanding why a mean field approximation is a sensible way of looking at students requires some shared understanding of many-body physics, and how averages of students might map onto a mean field in this analogy. Without extended engagement in a physics or PER community, outsiders could misunderstand the meaning of this metaphor.

Ethnographers not only attend to communities over long periods of time, they also aim to understand the natural ebbs and flows of participants' lives. This means taking into account overall patterns of activity in the community over the scale of days and weeks. In Summer Girls, the focus of my research was on the Arduino tasks that lasted 1-2 hours per day. I also participated in the broader camp activities, including courses, lab tours, and social activities. This helped me understand how the Arduino activities connected to the overall flow of the camp, and how the interactions in other settings may have contributed to what was happening in the Arduino setting. Within the 299B seminar, I observed students *in situ* in their research settings as well as the classroom. In interviews, I also asked about other aspects of students' physics experiences such as coursework, student groups, and extracurricular activities. Additionally, I have been a member of the broader physics community for almost nine years, which has also informed my analyses.

Ethnographic approaches help us understand equity—Ethnographic studies in undergraduate STEM have contributed to our understanding of equity. These studies have revealed which students have access to the valued practices and identities within the discipline and the mechanisms by which people leave disciplines. For example, in Tonso's study of an engineering school, she embedded herself within teams in design courses to understand what the valued identities are within the campus [33]. Within this campus, students described several explicit labels for students who were competent at engineering (e.g. "nerd," "overachiever"), and several labels for students who were competent in social and leadership roles (e.g. "sorority woman"). Women at the school were only recognized in the socially competent roles, whereas men could be recognized as socially or academically competent (but not both). Tonso described one case study, Marianne, who possessed many of the characteristics of the "nerd" category; she made significant engineering contributions to her team, and her team often asked her to do engineering tasks. Marianne was nonetheless not recognized by teammates and the instructor as being a competent engineer. This study complicates the common recommendation that giving women authentic engineering experiences can support gender equity in engineering; it is also necessary for the culture to recognize the authentic engineering that women do in these experiences.

As another example, Margolis and Fisher's ethnography of the computer science department at Carnegie Mellon specifically looked at gender differences in programming [7]. They identified many aspects of the computing culture that were on average more harmful to women than men. For example, it was valued to be "at the computer 24/7" and most out-of-class student conversations centered around computing. They found that many (one-third of) men did not align themselves with this stereotype but two-thirds of women did not align themselves with the stereotype. Moreover, women were more likely to take this misalignment as evidence that they did not belong in computing. This study points to harmful aspects of school culture that negatively impacts men *and* women, but can disproportionately impact women.

2.5.1 The ethnographic approach of my work

Within my work, I draw from several aspects of ethnographic methods in my analytical approach. My work follows participants for an extended period of time. I interviewed and observed students throughout the duration of the 2-week Summer Girls camp. In the 299B course, I conducted pre- and post- interviews and observational data collection during the semester of 299B, and conducted follow-up interviews a year after the course. My analyses integrate student interviews with my own participation in learning environments to strengthen my interpretations of each data set.

There are also some key differences between my work and the ethnographic studies that I have outlined here. Because I have been involved in classroom design, my research is inherently interventionist, compared to the typical "fly on the wall" ethnographic approaches. I deliberately designed classrooms with the goal of increasing access to STEM.

I also have developed case studies modeling a few students' trajectories or interactions, taking a person-centered ethnography (or "ethnography of the particular") approach. While ethnographic approaches have typically averaged across student experiences to look for commonalities, person-centered ethnography is an in-depth study of individuals within a culture [3,37,83], which foregrounds the unique aspects of an individual's experience as they move through a culture. Such approaches illustrate how small, sometimes idiosyncratic, experiences can have a cascading effect in students' broader trajectories. Averaging across student experiences and identifying which variables lead to their persistence and attrition can miss these small, but consequential events.

The person-centered ethnographic work that I conduct in this dissertation is not intended to be generalizable across the population of students. But rather, I specifically attend to the uniqueness of the case studies to develop mechanisms of learning that can be extended and refined in other cases. This builds what Eisenhart calls theoretical generalizability by refining theoretical mechanisms of how learning occurs [84].

Chapter 3: Tensions in the Productivity of Design Task Tinkering

3.1 Abstract

Tinkering is an ad-hoc approach to solving a problem and involves the practice of manipulating objects to characterize and build knowledge about a particular system in an exploratory way, often with the goal of getting some product/idea or to produce desired behavior. Tinkering contrasts with more deliberate activity toward understanding how some phenomenon works or toward achieving conceptual understanding. Some researchers have argued that tinkering is an unproductive process because it does not always lead to progress and/or conceptual learning. In this paper, we unpack the process of tinkering in order to speak to this tension regarding the productivity of tinkering for novice designers. First, we present a microanalytic account of two tinkering episodes to contribute to a more refined understanding of what tinkering is. Next, we claim that tinkering is not universally productive or unproductive. Through our analysis we illustrate how within a single episode, we can argue that tinkering behaviors help participants make progress toward some goals while hindering progress toward other goals. We argue that a more nuanced understanding of productivity, which takes into account a multiplicity of goals and actors, can lead to differing interpretations of the same events as productive or unproductive.

3.2 Introduction

Tinkering can broadly be thought of as an approach to problem solving characterized by iterative trial-and-error with the goal of producing some desired outcome or result. While there have been many varying definitions of tinkering (e.g. [85–90]), they generally share some common features. Tinkering consists of multiple trials which bring the user successively closer toward a solution [87,88]. Each trial is used to gather information about the system or observe some behavior which informs the next trial [86,89,91]. This contrasts approaches where one comes up with a plan ahead of time and then implements it [39,88,92]. Rather, the tinkerer plans as they go and adapts to the feedback of the system.

Tinkering has gained considerable traction in the informal learning research community. The Maker Movement, which fosters a democratic culture of creating and inventing, has celebrated tinkering as a valued practice. Researchers of these and similar informal learning environments have suggested that tinkering can support more authentic engagement in design than is found in traditional engineering classrooms, as it leaves room for learners to pursue their own interests and goals [93,94]. These learning spaces encourage what Papert called constructionism, the process of learning through creating and sharing material objects [95].

Tinkering has also been discussed as a potential way to increase access to STEM, especially within the Maker Movement [88, 93]. However, some research suggests that whether one engages in tinkering may depend on gender. A study by Jones et al. suggests that boys are more likely to tinker spontaneously while girls are more likely to follow directions [96]. Beckwith et al. similarly found that women are less likely to tinker than men, and that increased tinkering was associated with increased understanding for women but not men [85]. Gendered differences in tinkering in classrooms have been partially attributed to women having less experience working with tools and engaging in manual activities [97,98]. In contrast, work by Turkle and Papert suggests that tinkered approaches may come more naturally to women [39]. They first characterized bricolage (an iterative, adaptive approach to problem-solving that maps well onto tinkering [85]) as a female design practice and argued that men prefer planned, abstract approaches. They emphasize the importance of "epistemological pluralism"—valuing multiple ways of approaching problem solving instead of privileging planned approaches. While we question the notion that tinkering is an inherently gendered practice, we appreciate this line of research for emphasizing how some kinds of engagement in design activity may feel more or less comfortable to different students. This work motivates further research on tinkering as a practice, and how it may relate to equity within a design environment.

Tinkering is also worth studying because of recent national interest in promoting practices. The Next Generation Science Standards (NGSS), which integrates engineering into all aspects of science, emphasizes teaching practices in addition to concepts. Some have argued that some components of tinkering and making are aligned with the engineering practices identified in the NGSS and corresponding Framework for K-12 Science Education [93,99,100] for example, problem definition and designing solutions. Quinn and Bell have further argued that the student agency fostered by these activities can also support engagement in other practices [100].

This proposed connection between tinkering and design, as well as recent interest in tinkering motivates a closer look at what tinkering looks like in the classroom. However, research on how tinkering emerges in student activity in classrooms and research of microanalytic descriptions of tinkering is limited. In addition, there is disagreement in the literature about whether or not tinkering is productive student activity. In this paper, we contribute to the research on tinkering by presenting fine-timescale descriptions of tinkering behaviors of students and using that to address the debate on whether or not tinkering is productive.

In the next section, we present a brief survey of the literature on tinkering. In subsequent sections we describe the context of the learning environment, data collection, and analysis methods. Within discussion of our methods, to better illustrate what tinkering looks like, we contrast a vignette that illustrates tinkering with vignettes of similar design activities, troubleshooting and brainstorming. Then we present our analysis of two tinkering cases; in each case, a student design pair engages in tinkering behavior. In the first case, tinkering happens to set the stage for more conceptual sensemaking. We highlight how tinkering both encouraged productive engineering practices and helped students engage in sensemaking. In the second case, we describe an instance of where tinkering was productive toward some ends but not others. Students self-generated and got stuck in an unachievable task, yet were still able to engage with disciplinary practices. We then present interview data from one student in the second case, to illustrate how tinkering may interact with students' emotional experiences. This is followed by a discussion of results and implications for research and practice.

3.3 A Brief Survey of Literature on Tinkering

In this section, we describe the different ways that researchers have characterized tinkering, and the connection between tinkering and design thinking. This brief survey of the literature helps us define how we use the label *tinkering* in our analysis. In trying to bound what we label as tinkering, we then distinguish tinkering from other activities that can look very similar but have subtle differences, such as troubleshooting and brainstorming. Finally, we briefly discuss the debate in the literature on the productivity of tinkering activities, connecting this debate with other debates on the productivity of learners' activities in science and mathematics.

3.3.1 Definitions of Tinkering in the Literature

Within design environments, the term "tinkering" has been used to describe a breadth of activities. Some researchers use tinkering to broadly refer to using any set of manual activities. In their study of community college engineering students, Baker et al. identify tinkering as "manipulating, assembling, disassembling, constructing, modifying, breaking and repairing components and devices" [97]. They measured students' tinkering self-efficacy by asking students to rate agreement with Likert-scale items such as, "I know how to use tools." They contrast tinkering skills with "technical skills"—abstract problem-solving skills such as modeling, applying theory, and data analysis. Richardson similarly defined tinkering to be manual activities (e.g. assembling, repairing, using tools) in her study of undergraduate design teams [101]. Students self-reported engaging in tinkering on a Likert-item survey. This was corroborated with classroom observations which looked for verbal markers of tinkering such as "measure," "assemble," "operate." In a study of high school students in Nigeria, Erinosho describes tinkering as playing or working with items broadly related to science or engineering (e.g. magnets, batteries, screws) [98]. What is common to these studies is that they define tinkering to be manual activities that involve engagement with tools and artifacts, and contrast tinkering with more abstract approaches, such as the application of conceptual knowledge or pencil-and-paper problem solving.

Other researchers have used tinkering to refer an unplanned and improvisational process, independent of the materials used. These other descriptions of tinkering activities typically capture an improvisational nature of the design activity.

For example, in their study of tinkering self-efficacy in computer debugging, Beckwith et al. describe tinkering as "playful experimentation" [85]. They characterize tinkering as performing an action and immediately undoing that action. In a study by Law of undergraduates debugging computer code, researchers identified tinkering as using multiple ad hoc trials-and-errors, rather than engaging in reasoning about a bug [87]. Relatedly, Jones et al. defined tinkering as using the tools "purposefully outside of teacher's instruction" [96]. They contrasted tinkering with student activity that directly following teachers directions. Within these studies, the defining feature of tinkering is an unplanned approach.

Some definitions of tinkering also emphasize the iterative nature of tinkering, where tinkerers cycle over variations of their actions toward a design goal. For example, Resnick and Rosenbaum operationalize tinkering as rapid prototyping, an iterative process of "continually reassessing their goals, exploring new paths, and imagining new possibilities" [88]. They contrast tinkering to planning, which is the use of more formal and abstract rules to plan before implementing. Instead, tinkerers develop next steps through directly engaging and reacting to the system. Similarly, Vossoughi et al. describe iteration as key feature, where iterations are "drafts—moments in the process of creation that offer insight and fertile ground for new ideas" [91]. These definitions are similar to what Turkle and Papert describe as bricolage—a problem-solving process which adapts and modifies the solution as one goes. Bricoleurs have close engagement with the system, responding to feedback from the system as they go—what they describe as "a navigation of midcourse corrections" (p.169). Within these definitions of tinkering as an iterative process, each unsuccessful trial is treated as an opportunity for improvement, rather than a failure. Researchers argue that this reframing of failures into opportunities can positively impact student engagement and ownership [39, 88, 102]. We explore the potential emotional impacts of tinkering as an iterative, improvisational process at the end of this paper.

Tinkering processes have also been operationalized through data mining. Berland et al. [86] used Learning Analytics, a process of collecting code snapshots and conducting analysis to understand patterns of student activity. This is similar to studies which use data mining to identify activities that users engage in to debug systems [103]. Using Learning Analytics, Berland et al. identified clusters of students' activity, which they labeled Exploration, Tinkering and Refinement. Within this study, tinkering was labeled as the unplanned, adaptive process of trial and error to accomplish subgoals within a larger design goal. In a different Learning Analytics study, Blikstein et al. [92] identified tinkering and planning as two distinct programming styles by measuring the quantity and spacing of code changes. They operationalized tinkering to be making small frequent code changes, whereas planning was defined by longer, spaced out changes.

Others also partly define tinkering as an orientation, or overall approach to the activity. In their book about making and tinkering, Martinez and Stager [102] describe a tinkering as having an orientation of playfulness. This sense of tinkering being playful or informal is common in other definitions of tinkering as well [88, 91, 94]. For example, Vossoughi et al. [91] describe tinkering as a "disposition" of "iteration and playful experimentation." Wang et al. [94], in their study of an engineering exhibit in a science museum, explicitly define tinkering as "playing with and exploring materials and making things." In their definition of tinkering, this "playful" orientation is an exploratory, open-ended approach that supports the tinkering process.

Some researchers differ on whether or not tinkering requires a design goal. For example, some say that tinkerers have a specific goal in mind. Some describe these goals are user-generated and defined [93,94]. Others study tinkering in the context of goals which have been defined for the student or user [87]. Some researchers describe tinkering as a process that can occur without having a goal or design problem to solve [85] while others have described tinkering as having no explicit goal [104].

In a different vein, tinkering has also been discussed in the professional world. In their study of recognized policy and management innovations, Sanger and Levin [105] described how many innovations emerge through "evolutionary tinkering"; an approach of trial-and-error and combining bits of knowledge in a way that is responsive to the local context. They found that innovations were less likely to emerge from "revolutionary breakthrough" or through a more systematic analysis of data. This is aligned with other studies on professional design, which has suggested that teams that iterate often produce the best designs (cf. the Marshmallow Challenge [106]).

3.3.2 How Tinkering Relates to Design

While the term tinkering is not widely used in engineering design literature, tinkering shares some commonalities with descriptions of design. Tinkering is consistent with Roth's [107] description of the design process. In his study of elementary school children's engagement in design tasks, he showed how a given design is reflective of the classrooms tools and constraints. In this framework, a designed artifact in-progress is influenced by prior iterations of that artifact, and will influence future iterations. This process of having the artifact undergo evolutions is consistent with the adaptive, responsive nature of tinkering.

Dym et al. [108], in their study of undergraduate Project-Based Learning environments, similarly describe experimentation as an important aspect of the overall design process. They argue that "the design of systems is rarely accomplished exclusively by applying fundamental scientific principles" but rather, experimenting with materials is also important for design. Including this experimentation process, which helps generate information about the specific system, is consistent with the adaptive nature of tinkering.

In his paper about design thinking, Brown [109] does not explicitly discuss tinkering, but his description of the design process involves rapid prototyping—building preliminary models of a design, which is used to test and refine a design. He describes—"the goal of prototyping isn't to finish. It is to learn about the strengths and weaknesses of the idea and to identify new directions that further prototypes might take" (p. 3). Brown describes an iterative process of developing prototypes early on, and using tests to improve upon the next iteration of prototypes. Guerra et al. [110] describe how the UTeachEngineering team developed their version of a design process from existing design processes in the literature. Their cycle differs from other descriptions of the engineering design cycle in that it includes a cyclic subprocess of refining the concept, testing and evaluating the concept, and embodying (prototyping) the concept [111].

While none of these examples explicitly describe design as "tinkering," the iterative process of building, testing, and refining that characterizes the design process shares similarities with definitions of tinkering. There could, however, be a difference in the scale of time at which the iteration occurs within design. In rapid prototyping, for example, the idea is for the iterative refinement to occur at very short time scales (on the order of minutes) which can contrast with the iterative cycles represented in the design process as a whole (which can sometimes occur over longer time scales). However, they both draw on the underlying orientation toward iterative refinement that also characterizes tinkering. These descriptions of the design process and of design thinking thus incorporate steps (rapid prototyping, experimentation) that are aligned with tinkering. Other researchers have also described tinkering as a productive way to promote other design practices such as those in the Next Generation Science Standards (NGSS). Quinn and Bell [100] have suggested that tinkering promotes two steps of the engineering design process—problem scoping and designing solutions.

Another commonality between design and tinkering is that both activities happen in the service of a goal. A design problem is open-ended and the criteria for a design solution's success is ill-defined [112]. This is different from other settings, in which the goal of an activity is to apply or learn content knowledge. Within design, the practices and activities that students engage in happen in service of this design goal; applying science concepts and learning content knowledge only happens if it serves the design goal. Similarly in tinkering, the primary goal is to make a system or product achieve a certain outcome, rather than knowledge-building being the goal [86].

In this paper, we define and treat tinkering as both a process and an orientation. A tinkering orientation refers to a holistic sense of how students approach the activity. We align our definition of a tinkering orientation with Vossoughi et al. [91] and Martinez & Stager [102], who associate tinkering with a playful approach and general sense of trying things out. Processes of tinkering are often messy to identify, but we operationalize tinkering to be an ad-hoc trial and error [86, 87]. Tinkering involves the rapid prototyping of ideas, and information gathered during each prototype drives subsequent trials [39, 91, 109]. We contrast tinkering with deliberate sensemaking, which is a more systematic and planned activity. Though some researchers characterize tinkering as being with or without a goal, we define tinkering as having some design goal that can be prescribed or emergent. In our definition, the goal of tinkering is to produce a product or outcome, though the specific goal might shift during the activity. This contrasts other kinds of design goals, such as developing deeper conceptual understanding. Rather than having a goal of conceptual understanding as an end in itself, in tinkering the goal of producing an outcome can drive conceptual sensemaking—that is, conceptual sensemaking only happens in service of the outcome.

To summarize, though there are many definitions of tinkering, there are some commonalities across them which also represent the spirit of tinkering as we define it in this paper. Tinkering involves a non-abstracted engagement with the system. It also involves prototyping or iterative repeated trials. These trials provide immediate feedback which informs future trials. When tinkering, one flexibly improvises, which contrasts approaches in which one develops an abstracted plan and then implements it. In the next subsection, we describe how our definition of tinkering is different from similar kinds of activity.

3.3.3 Separating Tinkering From Similar Exploratory Activity

To clarify how we are thinking of tinkering, we now contrast tinkering with other kinds of student activity that seem similar to tinkering. Our purpose in presenting these is to help articulate (1) what tinkering is and (2) how it differs from other design activities that share some commonalities with tinkering but on deeper look, are different.

3.3.3.1 Troubleshooting

Troubleshooting [113,114] arises during engineering design implementation and prototyping when a system isn't quite functioning in the way that it is supposed to be or when a working system fails and the engineer needs to make it operational again. Troubleshooting is diagnostic in that the engineer proceeds to analyze where the flaw lies in the system and fix it. Instantiated in the course of an engineering design activity, the approach of troubleshooting doesn't change the overall feel of the design or the solution; once the faulty component or subsystem is fixed, the designer can proceed with the earlier design plan. Troubleshooting can, at times, look like tinkering since both can involve trying out multiple strategies, often in rapid succession, and where steps involve manipulating or probing the system in some way and acting on or refining ideas based on the feedback. On the other hand, we don't think that systematic and (at times) extended modeling of a system, which plays a role in troubleshooting [113], would be a practice that characterizes our definitions of tinkering.

Where we see the greatest divergence in these two activities is in how an engineer might construe the specific goals when tinkering or when troubleshooting: for tinkering, the goal is to solve an engineering design problem, to create something new; for troubleshooting, the goal is to fix or make functional an already fabricated component or system. We also anticipate that in tinkering the goals might be emergent and shifting while in troubleshooting, the goal is likely more stable/unchanging. So, at least in the context of engineering design, the purpose of troubleshooting is to restore the system to a working solution state while the purpose of tinkering is to push the system into a new imagined solution state. As we later illustrate, these differences in the goals/purpose are visible in the flow of design activity.

3.3.3.2 Brainstorming

Brainstorming is another activity that is integral to engineering design [115], in which the purpose is to come up with many different ideas for solving a problem ("problem" here could refer to a wide range of issues a designer might face, from very open ended tasks such as creating a better coffee maker, to something more specific such as fixing a particular circuit that has stopped working). Brainstorming often involves engaging in divergent thinking [108], similar to "shopping for ideas" [116], in that the goal is to come up with multiple ideas, deferring the selection of ideas to implement and the implementation details. Since brainstorming also involves playing with multiple ideas in the pursuit of a solution to a problem, it can, in specific moments, look like tinkering. However, brainstorming does not involve the prototyping or testing of ideas, and as such it typically does not involve iterating on the same idea (though successive iterations of brainstorming segments could surely involve iterating on an idea) in response to feedback from the system.

Tinkering, troubleshooting, and brainstorming are all activities that can happen during engineering design, and they share some finer grained similarities. We also don't mean to imply that these are disjoint activities—indeed, they can often be successively linked, or even nested (one could imagine brainstorming leading up to tinkering as one moves from ideation to prototyping, or a brief episode of brainstorming within a larger episode of tinkering or troubleshooting). It is this overlap between them, even when the goals of each activity are different, that we feel necessitates empirically distinguishing them in the flow of design activity, especially if the instructional attention is toward productivity. The divergence of goals becomes important when evaluating if a particular classroom activity is productive or not, because as we argue, the question of productivity hinges on answering the question, "productive toward what?" In this paper we start by empirically trying to establish a segment of activity as tinkering before attending to its productivity or lack thereof.

Attending to these differences in design activities can be helpful toward locating where students are in the design process. The design process can be broken into several design practices including brainstorming, troubleshooting, and tinkering [109,111]. Within science education, clear descriptions of scientific activities has been useful toward developing descriptive accounts of students' activities [117], making claims about the authenticity of students' activities [118,119], and understanding how certain patterns of activities can support some learning goals [48,120,121]. Similarly, identifying where students are in the design process can be useful for making ethnographic accounts of students engaging in the design process, and developing claims about their engagement and potential future learning trajectories.

Each activity within the design process has a different goal associated with it. Being able to quickly identify each design activity, and the goal associated with the activity, can help instructors and researchers make claims about whether or not students are making progress toward these goals. For example, within troubleshooting, designers typically are working with a desired outcome or solution in mind, and are orienting toward solving an error or fixing a problem. Troubleshooting does not lead to an overall change in the design, whereas in tinkering, the design itself evolves through trials. Within brainstorming, the orientation is toward getting many design ideas on the table with the intention of narrowing these ideas at a later point in time. Because brainstorming is a part of the ideation of the design, it does not involve trying to assess the feasibility of each design idea through prototyping. These assessments of feasibility and prototyping follow from brainstorming.

Being able to distinguish these design activities can impact whether and how an instructor might intervene. For example, an instructor might notice students getting "stuck" in a brainstorming mode, generating many ideas for an extended period of time without getting to test them. Noticing that students are spending too much time brainstorming, and then shifting students toward tinkering could support students in uncovering unexpected challenges or gaining knowledge about the system through prototyping. This shift in activities could be productive toward solving the design problem and developing deeper knowledge about the system. As another example, an instructor could notice students spending an extended period of time troubleshooting an error, and could encourage them to brainstorm new design ideas. This could be productive toward them generating a new design solution. Making these distinctions can helping instructors notice what students are doing, for the purposes of evaluating the extent to which students can make progress toward some student and instructor goals.

3.3.4 Prior Characterizations of the Productivity of Tinkering

Within the limited literature in learning sciences and discipline-based education research on tinkering, researcher opinion seems to be divided on whether tinkering is productive or not.

The case against the productivity of tinkering seems intuitive: tinkering could at times look like aimless or random manipulation of a system, or some might worry that tinkerers lack a deeper understanding, or worse: tinkering could encourage solving a problem without really understanding the deeper mechanisms. In a study of novices and experts engaged in debugging, Law [87] argues that tinkering did more harm than good, introducing additional bugs, and leading to more over-corrections than in planned approaches. Yeshno and Ben-Ari [90] also suggested that trial and error is only useful if it leads to conceptual learning. As Hancock [122] discussed, some instructors have claimed that tinkering might lead students to not engage with the underlying concepts of the activity. Rather than tinkering, they would rather students engage in planned exploration and conceptual sensemaking—in which the goal of the activity is to develop more generalizable conceptual understanding of how something works.

Yet, other researchers have mounted a defense of the productive role of tinkering in learning, especially in self-directed environments such as Makerspaces. One argument is that tinkering can serve a productive role in leading learners to the kind of sensemaking, integrated knowledge, or planned product that the other researchers seem to value. In their study of students learning to program, Berland et. al. [86] situate tinkering as an essential step between students' initial exploration phase and refinement of ideas. Hancock [122] argues that tinkering helps students develop pieces of knowledge which they can integrate more systematically at a later point in time.

In a different vein, Turkle and Papert argued for bricolage as a valid practice in itself, its productivity not dependent on whether it leads to a planned activity or not [39]. They argue that some ways of knowing, such as bricolage, are more authentic in some situations for some people, and stress the value of multiple ways of knowing and learning ("epistemological pluralism" p. 161). Turkle and Papert illustrate how bricoleur approaches lead to innovative solutions to design problems in computing, which might not have arisen if tinkering with programming was not an allowed option for the learners. They also highlight the unique affordances of tinkered approaches, such as helping students move past roadblocks easier. The overemphasis in learning environments on planned sensemaking, they say, can push away a diversity of learners from engaging in programming. They argue that allowing students to engage in activity that is authentic to them is important for their long-term engagement. Vossoughi et al. [91] make a similar argument: "This emphasis on iteration helps to reframe mistakes' or failed attempts' as drafts—moments in the process of creation that offer insight and fertile ground for new ideas."

What we notice here is that opinion is not only divided on whether tinkering is productive, but implicit in it are different researcher views toward what constitutes productivity (valuing in the moment activities versus how they relate to educators' longer-timescale goals) and conceptualization of authentic disciplinary practices (does iterative exploration count as engineering?). This tension on productivity and disciplinary practices are not unique to the topic of tinkering, but have been richly debated in science and engineering education research. While many science education researchers have valued the acquisition of content knowledge and scientific skills, others have also argued for the importance of engaging students in authentic practices such as mechanistic reasoning [123] and argumentation [14, 124]. Other researchers have valued students' epistemic agency [6], identity development [125], development of interest [126] or motivation [127], and of supporting students' disciplinary affect [128, 129]. These authors challenge the idea that conceptual understanding should be the primary goal in science learning, arguing instead that learners' development of scientific practices and dispositions toward science can be valuable in and of themselves. What this difference in goals leads to, however, is a difference in how one would characterize productivity, especially as these goals can often be in tension with one another. Careful accounts of teaching practice articulate how teachers often have to balance multiple, emergent goals in making judgments about whether learners' unfolding mathematics or science discussions are productive and use that judgment of productivity to decide on how they should act in a particular moment [116, 130].

Within a design environment, students and instructors similarly have a multiplicity of goals. As in professional engineering, students and instructors may have goals related to the quality of the final design of a product. There may be the goal of engaging in authentic engineering practices regardless of product quality, such as metacognitive reflection about one's design [131], and negotiating problem criteria [112]. There also may be learning goals that are independent of the product, for example, learning about the design process or some piece of content. Teachers may have additional goals on top of this such as positive affect, student agency, or positive identity alignment with the discipline. All of these goals can emerge at different times.

In addition to these goals, students and instructors are also dealing with classroom constraints. Many of these goals are often in tension and are limited by time and resources. Together, these goals and constraints are a dynamic system that instructors are constantly reassessing and responding to. Thus, when researchers label an activity as "productive," it is likely productive toward some ends and not others. For example, an instructor teaching a design-based summer camp might value a constructionist approach of students figuring out computer programming on their own; however, this instructor is also limited by time and does not want students to lose interest or to struggle through the fine details of computer programming. This instructor might choose to lecture students about computer programming basics, a decision that is productive toward allowing students to move more quickly to complex ideas, but is unproductive toward engaging students in early creative exploration.

With respect to tinkering, the debate around its productivity recognizes the affective benefit resulting from tinkering (in promoting engagement, for example) but seems to result in opposing viewpoints with respect to whether tinkering in itself contributes to learning. In this paper, we provide empirical evidence that tinkering can play a productive role toward some learning goals. We first add to the discussion on tinkering by presenting analysis at a finer time-scale than has previously been conducted in other studies of tinkering, in order to paint a clearer picture of what tinkering looks like in a classroom. We then argue tinkering can be productive toward some of the design goals toward which others have argued tinkering is harmful. For example, we show how tinkering can help students make progress toward their design goals and in some instances, even support engagement in more systematic sensemaking. We also suggest that there is more to be gained from tinkering than possibly conceptual skills. We don't mean to suggest that tinkering is universally productive or universally unproductive. Rather, we think that through fine-grained analysis of episodes of tinkering activities embedded within a broader task, researchers can get a better handle at how to characterize productive or unproductive tinkering behavior. Detailed examples of how tinkering plays out in engineering design learning environments can also help provide teachers with resources for recognizing tinkering, making judgments about the productivity (or not) of tinkering, and generating instructional strategies toward scaffolding productive behaviors in the classroom.

3.4 Analytical Flow and Context

We now turn to describing the context of our data collection, data streams, analytical workflow, and analysis methodology.

3.4.1 Classroom Background

We designed and ran a project-based instructional module within Summer Girls, a two-week summer camp for high school students organized by the Physics department at the University of Maryland, College Park. Traditionally, the summer camp included discussions on physics, short lectures and experimental demonstrations in physics. In Summer 2013, Quan got an opportunity to incorporate a project component centered on the Arduino microprocessor. The camp used an Arduino fitted with tank treads (See Figure 3.1) where the motion of the tank treads could be controlled by the Arduino, (henceforth, Arduino-bot). Gupta consulted with design ideas for the module. The module was piloted in Summer 2013, and small modifications were made and implemented in Summer 2014. Roughly 1-2 hours per day over the two weeks were dedicated to Arduino-based design activities, while the rest of the time was spent on modern physics lectures, lab tours, and demonstrations.

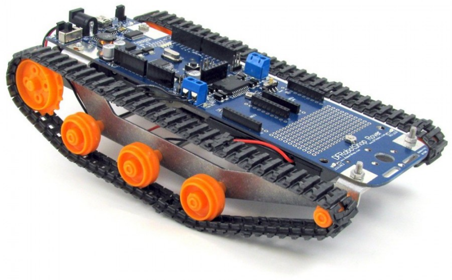

Figure 3.1: Arduino fitted with tank treads, purchased from Robot Shop.

For the project component of the camp, in the first week, participants worked in groups of twos or threes through several open-ended Arduino design tasks. Design tasks started with introductory activities to control Light Emitting Diodes (LEDs) using the Arduino-bot and moved on to more difficult tasks of programming the Arduino-bot to to perform some task such as detecting an obstacle, visually depicting distance from a wall, etc. The camp was co-taught by two instructors. Each day, there were 2-3 graduate and undergraduate student volunteers to help students attending the camp with their projects. Students were also given a reference library of sample code, and were strongly encouraged to reference the internet and ask each other for help. Students in the pilot year assembled into different teams (pairs/trios) every day in the first week of camp. In the second iteration of camp, most team compositions did not change throughout the two weeks. Once students had some experience with the Arduino and some electronic components, they were asked to work in teams to come up with a project idea that they would like to execute over the second week. Instructors didn't interfere with students' conceptualization of the project but offered help when asked for. In the second week, students built and tested their projects during the project time.

The project module was structured to allow for a high level of student agency. The design tasks were self-paced and there was no formal accountability or evaluative system for completing them. This encouraged students to assess their solutions themselves rather than to have them be evaluated by an authority figure [132]. Tasks were intentionally open-ended so that students were able to define and generate solutions to the design problems in pairs. Instructors also encouraged students to pursue creative ideas while completing the design tasks. For the final project, students were given the freedom to design any kind of final project they could think of using the Arduino, spare circuit parts, and anything they could scrounge up. Many students incorporated their interests into final projects (for example, a student in marching band made a "singing, dancing robot"). Students' readiness to pursue creative ideas, judge the quality of their own ideas, and figure things out on their own suggested that students had agency in the classroom.

3.4.2 Data Collection

Over two iterations of camp, we collected interviews, written artifacts (e.g. project proposals), and classroom videotapes of focal groups. Due to limited resources, we filmed classroom activities of one pair per day in the pilot year.

In the second iteration of the project module implementation, two graduate student colleagues, Stephen Secules and Erin Sohr, helped in the data collection as as classroom videographers and interviewers. Our plan was to conduct interviews with each student at the beginning of the camp, beginning of the second week of camp, and after camp ended. Only two students completed all three interviews. We filmed two groups of two students and two groups of three students during their group project activities. We collected classroom videotapes of all Arduino activities, and some additional in-class activities. We also collected some written work, including daily written feedback, of all consenting participants. Appendix C describes our collection of video data.

3.4.3 Analytical Work Flow and Methodological Orientation

After the pilot year, Quan took the first pass at viewing the classroom data to identify rich segments of students trying to solve a complex Arduino-programming or circuits problem. Quan identified one classroom episode of Hazel and Silver working together in the first week of camp as particularly interesting because students seemed highly engaged while problem solving. Quan brought this data clip to a science education research group meeting, for the group to brainstorm some preliminary analyses of what was going on in that data. During this conversation, the group characterized Hazel's and Silver's problem solving approach as "tinkering" and debated whether Hazel and Silver should have instead been engaged in more systematic conceptual sensemaking. We then used the data and existing literature on tinkering to develop working definitions of tinkering and conceptual sensemaking.

After the data collection in the second iteration of the summer camp, Quan selected Coral and Bianca as another focal pairing because of the large amount of data available for them. Quan watched the entire set of classroom video of Coral and Bianca and tagged other episodes which loosely fit with our working definition of tinkering. For tagged segments, Quan constructed analytical memos, describing the activities and categorizing students' epistemic goals (e.g. completing a task, understanding a concept). At this stage, we did not adhere to a particular methodology, loosely drawing on tools of knowledge analysis and interaction analysis [133–135]. In particular, the attention was on characterizing the bids students were making toward solving the problem, and the nature of their engagement with the computer and/or the Arduino-bot (e.g. typing code, interpreting code, manipulating the Arduino-bot, observing the Arduino-bot's behavior). This process of incorporating more data, and using our intuitive senses for tinkering helped us refine our definition of tinkering [136].

The interview audio-video records were similarly tagged for segments where the students discussed their efforts at tinkering or referenced the tagged classroom events. Interview data was used to refine claims about students' orientation or approaches to the activities and affective aspects of engaging in tinkering-like processes.

Next, the most promising segments of video from classroom and interview data were brought for group video analysis at meetings for two research groups (one in which members were engineering educators and engineering education researchers; and another where members more broadly drew affiliation with STEM education). Group discussions varied from comments on what different participants noticed in the data, to arguments on alternative interpretations of students' goals, and how the data supports or refutes those interpretations [133]. In between the group video analysis sessions, Quan, either working alone or with Gupta, created thicker descriptions of the data, with progressively refined arguments [136] for recognizing when students are engaged in tinkering and whether and how we could characterize the productivity of that activity. In this refinement phase, we drew more heavily on tools from interaction analysis [134] to construct fine time-scale analyses of the data. This line-by-line analyses of transcripts and associated video segments helped us identify within a given moment 1) the substance of the problem that students are trying to solve, 2) their approach to solving that problem, and 3) how their activity is negotiated. In doing this analysis we coordinated the substance of participants' talk with sequential turn-taking, paraverbal markers such as tone and prosody, gaze, posture, and gestures. Analysis at this timescale was particularly important because we were interested in understanding how the turn by turn interactions maintained the tinkering orientation, and in describing shifts in strategies which happened sometimes on the order of a few seconds. Throughout our analysis, we characterized student activity within a given moment to describe the process of tinkering. However, we also characterized students' tinkering orientations as they came up. For example, students' reflective comments about their activity and negotiation of what to do next allowed us to make claims about how they were approaching the activity.

We engaged in this process with other episodes which felt similar but subtly different from tinkering, to tease apart the fine-grained differences which separated tinkering from other activities. As our analysis progressed, we presented the more refined versions at the research group meetings referenced earlier to explore challenges and alternatives to our interpretations and arguments, which led to further refinement of the argument with a view toward arguments and interpretations that were supported by the largest fraction of the data.

We present these detailed descriptions of our data for the reader to be able to better evaluate our claims. While our drawing on the methodological tools was a bit opportunistic, rather than strict adherence to some methodology, our orientation toward fine-grained descriptions of participants actions and interactions as a means to build claims about the nature of the activity and its productivity drew inspiration from other examples of such fine-grained descriptions in the literature [137, 138].

3.4.4 Data Selection

Quan tagged eight episodes across video data of two design pairs as containing some of the features of tinkering. After more detailed analysis, we selected the two episodes as focal episodes for this paper which we thought were the best examples of tinkering. Two of the other episodes were later characterized as troubleshooting and brainstorming respectively, and used to refine our description of tinkering. We contrast these tinkering, troubleshooting, and brainstorming episodes, to give a better picture of what does and does not constitute tinkering. Then we present data from one interview with a student from the second focal episode, to demonstrate how tinkering may also be productive toward fostering affective engagement. We only selected clips in which students' maintained joint engagement in tinkering, troubleshooting, or brainstorming activity. Within a group, it is possible that students may engage in separate activities simultaneously (for example, one may be tinkering while the other is not). However, we found that the shared robot and computer encouraged students to engage jointly in the same activity.

The purpose of this analysis section is to illustrate how we identify tinkering within student data. We first present one episode where students are tinkering. We then present an episode of troubleshooting and an episode of brainstorming.

3.4.5 Identifying tinkering in data

In this section, we present a fine time-scale analysis of students engaged in tinkering to demonstrate markers of tinkering. In this episode, Coral and Bianca are working on a task of having the Arduino-bot complete a "maze." The "maze" was a pathway of left and right turns, made of raised wooden blocks, and was set up in the back of the classroom. Their talk indicates that Coral and Bianca were treating the maze as having right-angle turns. They discuss strategies for navigating the maze as they collaboratively type in code to make the Arduino-bot move. They use example code that was provided to them but modify it slightly (for example, their talk indicates that they changed the pin numbers designated for the motor controls, likely based on what the actual hardware connections were on their Arduino-bot). We start this illustrative episode when Coral suggests that they first complete a 90 degree turn:

> Coral: >i think we should< actually (.) figure out how (.) it like (.)
> (Coral picks up the Arduino-bot and puts it straight in front of her, with a hand on each side of it)
> Coral: what the value is to make it turn like (.) a hundred ni- >not a hundred ninety< (.) ninety degrees.
> (Transcript conventions used are provided in Appendix A)

Coral's tone, her halting speech, suggests that this was not something that she had thought of or decided much in advance, but was an idea that was emerging for her in the moment. Bianca accepts Coral's suggestion and through their joint action over the next several minutes they try various ways to make the Arduino-bot turn by ninety degrees.

Coral follows up with a suggestion that they should modify the code so that it makes the motor on one side of the Arduino-bot turn forward while simultaneously making the motor on the other side turn backward (this is a standard strategy often used to make robots turn in place):

> Coral: to make it turn, \Bianca: oh shoot\ can you do one low, one high?
> Bianca: Yeah, Emerald had it yesterday on had to make it turn ninety degrees but I can't remember
> Coral: the values, no but it's different for every robot. A lot of times you have to test it.
> Bianca: Oh true, true. true dat.

The words "low" and "high" in Coral's utterance refer to the values for the direction of the motor in the code. Coral's response to Bianca suggests that she doesn't think that the code that worked for someone else can simply be copied for their Arduino-bot. She expects to have to fine tune the values to fit their Arduino-bot. At this point, the mouse and keyboard are being controlled by Bianca. She types as Coral directs her to make the change she had suggested for the motor control variables.

When they try to upload the code they encounter an error, which they diagnose as being due to an incorrect bracket. Bianca fixes that, and uploads again. Their gaze shifts from the computer screen to the Arduino-bot, which shows no indication of any motion. Bianca asks if the Arduino-bot is switched on and which motor is supposed to be turning. Coral, with her gaze firmly on the Arduino-bot, answers that the left motor is on, and the right one is off. Then she looks up at the screen to notice an error that has popped up. Bianca reads aloud the error "Not in Sync" and says she has no idea. As Coral's gaze shifts back to the Arduino-bot, Bianca makes some more changes on the computer and uploads the code again, this time resolving the "Not in Sync" error:

> Coral: Go. Robot go.
> Bianca: um let's see.
> (Bianca makes some changes on the computer and re-uploads the code)

> (4)
> (Her gaze is neither at the computer, nor the Arduino-both, when the Arduino-bot starts moving) (1)
> Bianca: WOO! whoa, okay!
> (Bianca moves to try to switch off the Arduino-bot)

The sudden movement of the robot surprises Bianca. She manages to pick up the spinning Arduino-bot and turn it off using the mechanical switch on its body.

> Bianca: WOO! whoa, okay!
> (Bianca moves to try to switch off the Arduino-bot; Both are looking at the Arduino-bot)
> Coral: Oh it's just turning around
> Coral: We forgot- Oh, we have to do a delay on it. I forgot.

Coral's utterance ("just turning around") suggests that something is still not okay in the Arduino-bot's behavior. The observation of the Arduino-bot spinning in response to the current code almost immediately suggests to Coral that they should have added a "delay" in the code. Right at this point, Quan (first author, who was also the instructor) walks by. Bianca and Coral recreate the spinning motion for the Arduino-bot. Quan observes it, remarks that "it looks like a great spin," and as she walks away, Bianca enthusiastically says, "Woo! we know how to spin." And Coral brings her attention back to the task of incorporating the "delay" in the code:

> (Bianca starts typing)
> Coral: let's try a delay of like (1) one::: second >just to see<

The long pause before Coral suggests "one second" and the hedge immediately following that "just to see" indicate that she is probably expecting to use this as a trial run to see how the system behaves when a delay is added. Here, Coral's orientation can be characterized as exploratory, trying things out and intending to make further adjustments in response to whatever happens next. This contrasts approaches where one develops a plan before implementing it. Coral and Bianca collaborate over several turns of talk in using the right syntax in the code, ironing out minor difficulties (such as making sure to put the brackets and punctuation in the right places in the code). After uploading the new code, the Arduino-bot again spins around in circles, leading to frustration but also reasoning about what to do next:

> Bianca: (looking at the Arduino-bot) What is your problem?
> Coral: Okay so. Oh because it's a loop so it just keeps going.
> (Bot runs into Bianca)
> Bianca: Ow!
> Coral: It's a loop so it just keeps spinning.
> Bianca: Alright well.
> Coral: So it spins for a second, and then it reads it again and spins for another second.

> Bianca: Oh so.
> Coral: Infinitely.
> Coral: How do you make it st– Oh you have to– uhh?
> Bianca: Then we should probably do like, and then go forward. Instead of turn.
> Coral: Ah yeah I guess so. You could probably just copy.

We note the subtle difference in the way they respond to their continued struggle in achieving their objective of making the Arduino-bot turn by only ninety degrees. Where previously, Coral had quickly made suggestions for what to do next, here she spends time verbally unpacking the Arduino-bot's behavior. Coral unpacks the continuous spinning into a discrete set of turns (spins, read again, spins, and so on), which integrates the Arduino-bot's behavior with the code. This likely suggests to Bianca on how to break that continuous cycle (Bianca's statement starting with "then" closely following Coral's explication), by making it go forward at the moment it reads after a turn. Coral almost immediately accepts that suggestion and suggests a strategy for implementing this new idea for helping them get closer to their original goal of making the Arduino-bot turn by ninety degrees—copying and pasting the code from before. In the next 30 seconds they implement this idea and it works—the Arduino-bot turns and then moves forward and then turns again and so on:

> (Bot turns and goes straight, turns and goes straight)
> Bianca: Yayyy!
> Coral: We have to try and figure out what the angle is so–

The immediacy by which they continue on, with only a short pause to celebrate, suggests that they don't really consider their goal achieved, but rather the task of making the Arduino-bot turn and move forward was in service of their bigger goal of achieving a ninety degree turn. The pair then spends almost 4 minutes adjusting and re-adjusting the delay (the amount of time spent in the turn) over several trials, making smaller and smaller changes. Throughout this process, they are making rough estimates of changes to the time delay, and they do not systematically try to calculate a value.

We label this entire episode as one of tinkering. At the start we see the emergence of the goal of wanting to execute ninety degree turns. They rely on the example code provided to them and their knowledge about the Arduino-bot's hardware connections to make it start spinning first. In doing this, they had to solve a few minor syntax and interface problems. But this leads to the emergence of the new unanticipated problem—that the Arduino-bot keeps spinning. In turn, that leads them to try out a variety of strategies, adding a delay, fixing code syntax, adding a subroutine to make the Arduino-bot to alternatively move forward and turn, and finally to fine-tune the time for which the Arduino-bot is commanded to turn as a means of achieving the ninety degree turn. Their activity is fast-paced; every failed move generates the next move almost immediately. As soon as an idea is suggested they move to try it out; they don't pause to fully discuss the pros and cons of each move or to create an argument for why it would or wouldn't work. Moves are often generated based on the observations of the Arduino-bot's behavior in response to their last change to the code. And there is a conspicuous lack of detailed planning (they don't *a priori* engage in brainstorming solutions, or generate parallel alternative ideas, or detail an execution plan before engaging in action). It is this fast paced, action oriented (rather than planned), grounded in observation of the system behavior, and "one move leads to another" nature of the activity, all in the service of a design goal of making something new happen, that leads us to characterize it as tinkering.

This contrasts with activity in which students are looking for a quick fix or change, which we explore in the next subsection.

3.4.5.1 Separating tinkering from troubleshooting

To contrast the episode we label as tinkering above, we now present a segment of Coral and Bianca that we label as troubleshooting. This episode occurred on the second day of camp, and students had spent about three hours working on Arduino activities. Coral and Bianca are trying to fix their code to make the Arduino-bot move. This was embedded within a larger task of making the Arduino-bot move forward but stop when it came close to an obstacle. Coral and Bianca were testing the distance sensor they would use to detect the obstacle, but when they ran into some trouble in getting the appropriate behavior from the distance sensor, they temporarily abandon that task and focus on getting the Arduino-bot to move forward. Coral starts by copying and pasting segments of the reference code (provided to them by the instructors) into a new Arduino program. A graduate student helper, Stephen, is peripherally working with them. After typing in the code, they upload the code to the Arduino-bot but the Arduino-bot does not start moving. They spend the next nine minutes trying to figure out what is wrong with their code or with the hardware connections.

Bianca first asks (her gaze is on the screen and it's not clear if she is wondering aloud or asking Coral or the helper) if they correctly initialized the parameters in the code. Coral responds that they just set it to zero but doesn't know if that's correct. Stephen initially tells them that their initialization of parameters to zero is ok, but then after about 30 seconds says that the values for the parameters should be specific since they reference the motor connections. Coral and Bianca spend the next minute changing the values, coordinating and checking with one another to make sure they are putting in values they think are correct. Since there are four parameters, they are being very careful that these are assigned to the correct Arduino pins in the initialization routine. After typing in these values, Coral picks up the Arduino-bot and lifts and turns it, as if to check the hardware connections on the Arduino-bot. Their speech here is brief, interrupted, and interspersed with their handling of the Arduino-bot. Bianca takes out the wires that aren't needed for making the Arduino-bot move (leftover wires from the distance sensor testing) while Coral locates relevant components (as indicated by brief turns of talk, "This is the battery pack.", "oh! here's the motor."). It is as if they are trying to make sure that the motors are connected and there are no loose wires or connections.

Stephen encourages them to try out the revised code. They do so, with high expectation (Bianca exclaims in a loud voice, "GO!") but the Arduino-bot does not start moving. This leads them to turn back to checking the mechanical connections, this time more explicitly communicating their intent. Bianca asks if they need to hook up the motor as they jointly hold the Arduino-bot up in front of them, turned halfway upside-down so they can see the connections underneath. Coral says that the motor is hooked up, and points out the connections to Bianca. Coral asks if the battery pack is hooked up but it doesn't get taken up by Bianca, since Bianca was simultaneously identifying the motor connections on the top of the board. Next, they spend some time trying to understand the variables in the code which correspond to the motors: M1, M2, E1, and E2. They notice that M1 and M2 are labeled on the Arduino-bot but are unable to locate E1 and E2 on the Arduino-bot in the next couple minutes. Then Bianca suddenly notices an empty pinhole on the board and suggests that maybe another connection needs to be made. She shows how she would make the connection by holding a wire on the pin-hole location on the Arduino-board, but quickly abandons this idea without specifying why. Then, Bianca makes another bid for understanding M1 and M2, "What does that even mean M1, M2. What does that even mean?" Coral starts reading the lines of code off the screen that contain M1 aloud. Bianca then suggests that they ask an instructor or another student how to make it work. They discuss the problem with another student who had gotten her Arduino-bot to move. As they are talking to the other group, Stephen comes over to tell them that they forgot to include four lines of code in the initialization that would designate the Arduino pins connected to the motors as "output" pins. As they type these in, the instructor starts making some announcements for the next activity for the day, and they decide to save their code and try it the next day. The whole episode from the first time they test to see if the code would make the Arduino-bot move to the end of the segment (between which they try to figure out what's wrong and fix it), lasts about 9 minutes.

We labelled this segment of activity as troubleshooting. Their goal in this entire segment was to identify a fault in their original strategy and fix it, but not fundamentally change direction. To this end, they question their initialization values for the parameters, check to make sure they have batteries and motors connected properly, clean up wires left over from before, and check to see if the parameters specified in the code correspond to the connections on the Arduino-bot. This process of iteratively generating multiple causes and testing them is a characteristic aspect of troubleshooting. They seek help from instructors, and ask their classmates who have been able to make the Arduino-bot move. The troubleshooting activity shares some common characteristics with tinkering. They have a specific goal and try out many actions toward achieving that goal, but the difference is that these similarities are enveloped in different broader orientations toward the task. In tinkering, their broader orientation was toward improvisation in response to new behaviors that the system generated as they try our particular actions; in troubleshooting, their orientation is toward identifying the fault in their original execution and fixing it.

We now explore brainstorming as a similar non-tinkering activity.

3.4.5.2 Separating tinkering from brainstorming.

We present a segment that we tagged as brainstorming to contrast with tinkering activity. Coral and Bianca had decided that they want to create a cardboard dancing baby in which each foot is a separate Arduino-bot. This clip, which occurs in the first hour of implementing the final project, involves Coral and Bianca coming with ideas for how to use a light sensor in their design of the baby. Bianca was engaged in writing code to make the baby's foot move and trying to get Coral's attention on the task, as Coral rummages through the box of components. Coral fishes out a plastic bag with sensors and suggests they use a light sensor, a component they had not used yet. She adds on that the light sensor could be integrated into their project by using it to make the baby cry.

> Coral: Do we want to use the light sensor?
> Bianca: No.
> Coral: But like, Noooo oh my gosh! (Bianca opens her mouth really wide)
> Coral: We should like shine the light on the baby and then make it cry.
> Bianca: Oh my god! No!
> Coral: (Laughing) No?
> Bianca: How would we even do that?

The idea of using a light sensor comes as a surprise to Bianca and initially she seems resistant to the idea, expressing surprise that indicates that this seemed a strange idea to her. But soon she takes a more collaborative stance, asking Coral to elaborate on how this could be done.

> Coral: Using, okay. So you use the light sensor, \Bianca: Yeah \ which is this thing \Bianca: Yeah \ when you shine on a light on this you can say like if, and then the light, whatever value, \Bianca: Yeah\ is greater than whatever, do this. So it would be like when you shine the light
> Bianca: Yeah but how would we make it cry?
> Coral: It would activate the speaker which would have a recording of like a baby crying on it. And as soon as you like shine the light, so like put this on the baby's \Bianca: Yeah yeah I mean- I get\ the baby's eye so like when you shine the–

Coral explains how they could have their code check if the light sensor registered a value greater than some threshold ("light, whatever value, is greater than whatever") and use that condition to activate a speaker to play a recording of a baby crying. As Bianca starts understanding what Coral means, she starts to play with the idea too, suggesting where the sensor might be placed:

> Bianca: Or like right in between
> Coral: yeah
> Bianca: Like a bindi
> Coral: yeah. When you shine a light on the baby's, like, face, it cries.

> Bianca: That's so mean but okay, I guess we can do that. Let's work on the Arduinos first.
> Coral: Oh my gosh that would be so funny.
> Bianca: Wait but how would we hook it up from the robot all the way to the baby's head which is at least gonna be this tall.
> Coral: Okay maybe it's like when you shine the light on the baby's foot, it cries.
> Bianca: The baby's foot?
> Coral: Yeah! It's a weird baby!

As Bianca warms up to the idea, she notices that it might be challenging to physically have wires going from the Arduino-bot which is at the foot of the baby to it's head, which leads them to modify the plan and place the sensor on the baby's foot.

What started as a question for Carol (wondering if they should use a light sensor) soon turns into a brief episode where they generate ideas for how to use the sensor in a fun way. They share ideas without necessarily fleshing them out fully, imagine of how the ideas might be realized, and come up with additional variations to their scheme in response to anticipated difficulties. Hence, we label this activity brainstorming.

Here too we see some similarities with tinkering, in that they have a design goal (using the light sensor to make the baby cry), multiple ideas are shared to achieve it, and they modify their design in response to projected difficulties. But there are also differences, in that they are not actually testing or prototyping these ideas and there is no feedback from the system in response to their actions (their design revisions are based on anticipated problems rather than observations of the system), and their broader orientation is toward coming up with ideas rather than toward implementing a solution to a design problem.

To summarize, key features of tinkering involve having a design goal that is to complete some kind of task or produce some kind of behavior. Tinkering toward this goal looks like the rapid engagement of testing and receiving feedback from the system. Future trials are informed by feedback received. Tinkering is also improvisational. Each iteration opens up new solution space and possibilities for solving the problem. We presented contrasting episodes of troubleshooting and brainstorming, design activities that share some characteristics with tinkering but differ in the broader orientation and in the details of how actions are structured in each activity. We do not want to claim that these are completely disjoint or unrelated activities; often in the course of design, tinkering might lead to troubleshooting and vice versa or designers might transition from tinkering to brainstorming and vice versa. These activities can also be nested in one another. For example, in our episode on tinkering, when Coral and Bianca first try to upload the code, they encounter some problems (the "not in sync" error) and engage very briefly in troubleshooting. The troubleshooting is short-lived and they quickly return to their broader objective of making the Arduino-bot turn by ninety degrees. So, tinkering as a label, captures that episode as a whole. Thus there is a grain-size consideration in how we label an episode as tinkering.

3.5 Characterizing Productivity in Data

We now turn to our focal episodes where we analyze whether and how tinkering in the flow of design activities can be productive or unproductive or both.

3.5.1 Hazel and Silver: Tinkering Leading to Conceptual Sensemaking

Our first episode comes from a pair of students, Hazel and Silver, who were working through design tasks with their Arduino-bot. The episode begins when Hazel and Silver had just completed a short task in which they were asked to write a program to make the Arduino-bot move forward until it detected an obstacle/wall, and then make a right turn. When Hazel and Silver uploaded their code to the Arduino-bot and ran it, the Arduino-bot turned right at the obstacle but then it didn't stop. It just kept going and ran over the keyboard until Silver grabbed it. In response, they decided that they should make the robot stop after turning right.

This goal—to make the Arduino-bot stop automatically—is not something that was assigned to them. We see the goal emerge, in part, through interactions between the physical constraints of the space and the Arduino-bot: had Silver not grabbed the Arduino-bot, it would have run off the table and it's difficult to mechanically switch the Arduino-bot off as it is moving.

> (Bot goes straight toward a white box and turns when it gets very close to the box)
> Hazel: Oh, oh yeaaa!
> Silver: stop, stop, stop
> (After the Arduino-bot has turned, it keeps going and Silver is trying to flip the mechanical switch on the Arduino-bot before it runs over the stuff on the table)
> Hazel: That totally worked, that was so cool.
> Silver: So, like, could we make it stop?

Seeing the Arduino-bot run up on the stuff on the table generates an emotional reaction of wanting it to stop, as if something is going wrong or unintended and that the corrective action needs to be fast. When Silver suggests modifying the task to stop the Arduino-bot, Hazel immediately takes up the task and offered suggestions of how to make it stop. Later, other groups ask them if they had been able to make it stop, suggesting that other groups were also adding "stopping" to their task and thus reinforcing this goal for Silver and Hazel. The openness of the classroom culture in which students felt ownership over the project task also played a role in students feeling comfortable in modifying the task statement to include stopping—no group asked the teacher for permission to do this, and the groups of students decided how to spend the bulk of their class time. Thus the problem statement here emerges in students' interaction with the Arduino-bot.

We now turn to the segment of conversation and action that follows Silver's suggestion of making the Arduino-bot stop. They first begin by adjusting the parameters for motor control in the code.

> Hazel: We could just, we could also make it stop.
> Silver: Oh, like after it gets to this distance.
> (Both girls lean into the computer monitor as they speak)
> Hazel: We could turn these from, like, low stop.. I just changed this one to low.
> Silver: What was it before?
> Hazel: It was high. Cause if one [inaudible] (pointing to left tread) it makes it turn right.
> Silver: Oh. So low means off.
> Hazel: Yeah, same with the light, and brightness (points to the LED on the circuitboard).

We note the rapidity of their first attempt at trying to make the Arduino-bot stop at the obstacle. Even as Hazel was considering the option of switching code parameters from HIGH to LOW, she makes that change. This is something they had tried before when working with LEDs to electronically switch them on and off ("same with light, and brightness"). Here Hazel is building off of that experience to think how the motors might respond similarly. Hazel's and Silver's code here, however, consists of stitched snippets of example subroutines (snippets of programs) provided to them by the instructors. In the particular portion where Hazel makes the change, the HIGH and LOW parameters were determining the direction of the motor movement rather than its speed. This leads to unexpected outcomes:

> (Hazel uploads the program to the Arduino-bot, disconnects the wire from the computer to the Arduino-bot, and switches on the batteries on the Arduino-bot. They watch expectantly as the Arduino-bot moves forward, slows down, and runs into the box)
> Hazel: It's now trying to stop. Oh, no, no
> Silver: Oh, it's now turning low power to high to just like–stop. Do you think that's in the PDF?
> Hazel: Yeah
> Silver: Yeah
> (They open an Arduino-bot reference sheet on the computer)
> (10)
> Silver: Oh that's how they do (??) the with the distance sensor.
> Hazel: Oh, yeah. That's the number it's getting. (They continue looking at the screen in silence)
> (10)
> Silver: It doesn't say how to stop.
> Hazel: No, but that's a thing we can Google.

After their first modification does not work, they spend about 3 and a half minutes checking a reference guide and then search on Google for the solution, strategies which were encouraged in class. Briefly, in between, the group behind them (who was also trying to make the Arduino-bot stop) checks in with them to see if they had any success and asks them to let them know if they do.

After about 3.5 minutes, Hazel makes a bid for trying another thing: to turn both motor controls to LOW. Silver, in response suggests that they should just remove the lines that include the parameter M1 (technically, in the example code provided to them, M1 controlled the speed of the motor using a command called "analogWrite") to which Hazel readily agrees, saying, "yeah. Cause I don't know what analogWrite is." Hazel makes the modification and uploads the code to the Arduino-bot. When they run it, it just moves and rams straight into the obstacle. They notice and remark that the Arduino-bot "didn't even get slower."

Next, Hazel suggests including back the M1 statements, but changing one of the numerical parameters (technically, the numerical parameter determines the speed of the corresponding motor) in that statement. When she tries that the Arduino-bot turns when it gets close to the obstacle (which is as it should be: changing one of the M1 parameters would change the relative speed of the treads on the two sides causing the Arduino-bot to turn). However, this confuses them since Hazel didn't think that changing that number would have made the Arduino-bot turn. Hazel and Silver then go back to the example code and documentation shared with them by the instructors and try to carefully track the parameter values in the example code with the values they are using. They make another change and try to run the code again, but it starts to go in reverse when it encounters an obstacle, confusing them again. Part of the confusion here is that Hazel and Silver are interpreting the setting of the parameter that is set to LOW or HIGH as respectively denoting the conditions of "switched off" and "forward motion," while really the LOW condition sets the Arduino-bot to move forward and the HIGH condition sets the Arduino-bot to move backward (not stop). Unfortunately, this isn't easily discernible from the code itself.

They continue to work through trying out several code variations in the next 3 minutes, following a pattern in which they make a change, carefully observe the motion of the Arduino-bot and then try to interpret the observed motion in terms of the code, and then make another change to test their interpretation:

> Hazel: Okay. So we know that, that high was backwards, it is the reverse of what it's supposed to be.
> Silver: I think the distance part is messing it up now.
> Hazel: Okay, yeah.
> Silver: Maybe take out the distance part and see if it will go for, like a, certain amount of time, or a certain.
> Hazel: We have a delay here, I think that's what's causing things to be weird cause- can we have more than one [inaudible]? No.
> Hazel: So it takes a reading. It calls it for one second. It goes forward. It-
> Silver: [inaudible]
> Hazel: Cause it doesn't-

> Hazel: Yeah or I think it should stop in the beginning and take a reading...

As we can see in this segment above, their cycles of making changes, observing, and interpreting is gradually leading them to fix some of the bits of their understanding—they now have corrected their interpretation of the "HIGH" parameter state. In this cycle they also engage in systematic parsing of the code as we see above when Hazel tries to step through the code ("So it takes a reading...").

We see this entire episode as tinkering because Hazel's and Silver's exploration with the Arduino-bot is goal directed (they want to make the Arduino-bot turn and stop), and it involves "thinking with the object," [39] in which their ideas for next steps are closely intertwined with observations of how the Arduino-bot responded to their previous actions.

And we want to argue that this was a productive engagement for Hazel and Silver with respect to authentic disciplinary practices. Hazel and Silver engaged in "rapid prototyping" of their ideas in a way that is helping them understand deeply how their system responds to various parameter value settings. They used a wide array of strategies such as trail and error, coordinating the hardware and software, systematically parsing some portions of the code, reading code documentation, and using the internet. They coordinated the wide range of resources available to them including their friends, the instructional materials, and information available on the internet in order to sustain their engagement with the task. They built on each other's ideas, coordinated the sharing of resources and actions, and thus engaged in good teamwork practices. Furthermore, they were strategically and metacognitively engaged. Their activities reflect a certain level of judgment in the management of resources and time; they did not get fixated on any path, but quickly judged if the path would be productive, and if not, they switched tactics. Tinkering also helped them build conceptual knowledge; it helps them spot portions of the code that they do not fully understand, it gets them to explore (through making changes and observing the response) the functions of some of the code bits, and helps them repair their understanding of the function of some key parameter values.

One could argue that instead of tinkering, Hazel and Silver should have systematically parsed the code to make sense of it; they would have had better task success and better learned Arduino programming through that. Had they first tried to understand each code statement, they would have not had to go in this circuitous manner. We contest this notion. Through the tinkering exploration, Hazel and Silver are charting their own path to the solution and in the process, getting to experience various authentic engineering practices. Systematic parsing of the code right from the start would have had the trade-off of robbing them of those experiences. Thus the episode highlights for us the tensions of calling something productive or not. If the instructional goal is to have the students walk the fastest path to a solution having developed conceptual knowledge first and then applying it, then this segment might appear unproductive (or at least allowed to continue for too long). But if the objective is to engage students in authentic design practices, where progress toward solution and a deeper conceptual understanding of the system are made iteratively and in smaller steps, then the episode will appear as productive.

In the next section, we illustrate another example of tinkering and the emergence of a similar tension in being able to label it as productive or unproductive. In addition, we bring up the notion of how judgments of productivity are also associated with the issue of grain-size at which we evaluate student work.

3.5.2 Bianca and Coral: Disciplinary Practices in Tinkering

We now revisit the prior example of Coral and Bianca tinkering to make the Arduino-bot turn by ninety degrees. Our purpose here is to illustrate (i) how tinkering can engage students in productive disciplinary practices, even when it does not support them in producing a good solution to a design task and (ii) how multiple instructional goals may be in tension, motivating a nuanced understanding of productivity.

This episode comes from day four of the first week of Summer Girls. Coral and Bianca had just completed a task of detecting and avoiding an obstacle and had moved onto the next task of programming the Arduino-bot to navigate through a "maze." The "maze" was a pathway of left and right turns, made of raised wooden blocks, and was set up in the back of the classroom, and students had access to the maze for testing their programs as they developed it. Instructors had intended for students to adapt code they had previously written in which the Arduino-bot detected and avoided an obstacle. Instructors also intended for students to use a closed-loop control strategy to identify walls with the distance sensor, and use logic control structures to determine next steps when a wall is detected. [1]

At the start of the task, Coral says that the maze likely has 90 degree turns, and suggests that they first find the delay to complete a 90 degree turn. In this move, we see Coral strategically breaking up the large task of navigation into smaller subtasks, specifically identifying the 90-degree turn as the one they should execute first. This strategy of breaking a larger task into small testable pieces is often a good design practice, but in this case, it is also a difficult one because of inconsistencies in the Arduino-bot's motion over short timescales.

In the first three trials, Coral and Bianca try to make discreet turns. In the first trial, they realize the need to include a delay after the initial turn so that the Arduino-bot does not loop through the turn code continuously (this was described in more detail previously). Coral suggests turning the Arduino-bot for one second "just to see," indicating that she intended to observe how the system behaves. When they run the code, the Arduino-bot continues to turn in circles which leads Bianca to suggest that they need an additional "move forward" step. This additional step is necessary for them to be able to identify when a single turn is completed and fine tune the timing so that the turn is through an angle of ninety degrees. Note, what

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[1] A closed-loop control strategy refers to a strategy in which the computer program uses feedback to determine its next steps. For example, a program could say: Go straight until you detect a wall, then turn right, if a wall is detected to the right, then turn left. This contrasts to an open-loop strategy in which all of the steps are pre-determined and written into the code. For example, go straight for 1m, turn right, go straight for 1m, turn left.

they are doing here is making small changes to their current strategy in response to how the system (Arduino-bot) behaves in response to that strategy. It is a cycle of action, observation, reflection, and revision in which their actions and the Arduino-bot's reactions are coupled in mutual evolution. This instance is similar to what Turkle and Papert describe "a collaborative venture with the machine" (p. 136), treating the mistake as a part of their navigation toward a solution, rather than a bug [39]. Bianca adds several more lines of code to have the Arduino-bot move forward after it turns. The Arduino-bot successfully loops through the turn and forward motion, even though the turn is not 90 degrees.

> Coral: We have to try and figure out what the angle is so–
> Bianca: It was a little bit more than 90 so–
> Coral: So let's say it's probably about like
> Bianca: It's like 135, so we need it to be like 45 degrees less
> Coral: Right. So change it to like–
> Bianca: Should we change the delay to–
> Coral: Oh yeah you change the delay to like, 750. Wanna try that?

In this clip, they move from one aspect of their goal, getting the Arduino-bot to spin and move forward, to getting the timing of the spin. They estimate that the Arduino-bot turned by 135 degrees with the delay of one second (specified as 1000 milliseconds in the code) and decide that in order to make it stop turning at 90 degrees they would want the delay to be 750 (milliseconds), their time estimate drawn intuitively and without doing explicit calculations (technically, a calculation to reduce the time by one-third would have yielded 667 milliseconds whereas 750 milliseconds only reduces the time delay by one-fourth). This rapid change based on eye estimation and without carrying our calculations also suggests an orientation of trying things out as opposed to more planned activity. The pair then spends almost 4 minutes adjusting and re-adjusting the delay over several trials, making smaller and smaller changes, with each adjustment drawing on testing a delay value, observing the Arduino-bot's behavior and making quick changes to the delay time based on that. In one run, the Arduino-bot turns 90 degrees on the first turn, but in the second turn, it turns more than 90 degrees (as we noted before, the Arduino-bot has limited accuracy and reliability). Bianca starts to notice this inconsistency in how the Arduino-bot runs.

> Bianca: Yeah! That's like perfect. But how come when it does it the second time it doesn't?
> Coral: I think it was the cord. I think the cord was pulling on it.
> (Coral removes cord and runs again. The Arduino-bot keeps looping through the turn and forward motion)
> Coral: Oh that's a tiny bit more than 90 I think.
> Bianca: Why?
> Coral: See? Now that was 90! And that was a tiny bit more than 90?
> Bianca: Why is it so inconsistent?
> Coral: So it went from like here to like–

Bianca: Yeah.
Coral: It probably like, it's probably 775.
Bianca: Or maybe we should make it like 780.

In this clip, Bianca notices that the Arduino-bot doesn't turn for the same amount in each loop. Coral at first suggests taking out the USB cord, attending to how the physical setup could be causing variability in the motion. Bianca makes a bid to understand why it's so inconsistent, but they revert back to fine-tuning the delay. The period of rapid testing ends when Coral decides to look at the maze. She briefly consults with a classroom helper.

Coral: We're figuring out 90 degree turns
Helper: Awesome.
Coral: I hope the maze has 90 degree turns.
Bianca: Yeah that would be, it should be.
Coral: Is the maze up? Do you know?
Helper: I think so.
(Bianca uploads and runs another iteration)
Coral: It's a little bit–
Bianca: Why?
Coral: Cause like if starts like straight, it's pretty close.
Bianca: It's still gonna run into the wall though.
Coral: Well for now, we should probably actually like look at the maze. I'm gonna go–
(Coral gets up)
(Bianca types and tests new values on her own silently)

Coral's statement, hoping the maze had 90-degree turns and asking if the maze had been set up, suggests that they had not actually seen the layout of the maze at this time. At the end of this segment, Coral goes to look at the maze while Bianca continues to try to fine-tune the delay. Coral seems to be making a bid at the end for getting the turn "pretty close," because it might still go through the maze.

As they develop their project further, their approach to the maze-navigation task ends up being an open-loop strategy to turn and go straight, rather than developing an algorithm using a distance sensor. By "open loop strategy" here we refer to their strategy of where all the decisions for timing and direction are programmed *a priori* and fully specified in the code, for example, instructing the Arduino-bot to go forward for a fixed time, then turn in a specified direction for a fixed time, then go forward for a fixed time, etc. In contrast, a closed loop strategy would use sensors to provide feedback to the system with decision making steps. The code would execute decision-making on whether to turn or go forward, which direction to turn, and for how long to execute each step. Only toward the end of the task, they incorporate the distance sensor to detect when they have to make the first turn and to detect the end of the maze.

We now turn to discussing in what ways we can think about their actions here as productive or unproductive. In some ways, their goal and approach to the task was unproductive. Coral and Bianca were trying to fine-tune a time delay to get the Arduino-bot to make 90 degree turns. This goal is nearly impossible to accomplish based on how sensitive the Arduino-bot is to small perturbations, though they don't know that when they start to work toward it. Despite Bianca noting that the Arduino-bot turns inconsistently, they still stay engaged in this strategy, rather than shifting strategies.

This overall solution is not robust for several reasons: if the Arduino-bot is as inconsistent as they observe, then it might encounter problems in making multiple 90-degree turns accurately; if the maze is not set up with exactly 90-degree turns, that could lead to failure; or, if they can't perfectly assign the delay time for moving forward in each straight portion of the maze, the Arduino-bot would likely turn too soon or too late. Their timing delays are matched specifically to this particular maze, and their algorithm will need to be revised for any changes to the maze, needing just as much effort again in fine-tuning the time delays to take any variation to the maze into account. As such, an instructor who is interested in having their students use sensors to generate more general-purpose strategies for maze-navigation, might feel that Coral and Bianca did not capitalize on their observations of the inconsistency in the Arduino-bot's motion or use the distance sensor that they had previously been provided instructional resources for. Maybe if Coral and Bianca had engaged in a divergent thinking brainstorming session and come up with multiple strategies for making the Arduino-bot turn by 90-degrees, that would have helped them see the advantages and disadvantages of the different strategies. But Coral's initial suggestion of trying out what happens with a delay of 1 second and Bianca's approval of that suggestion sets them on a path to continuously adjust the value and ultimately implement an open-loop strategy. While our data underdetermines the reasons why Coral and Bianca did not switch strategies, it is plausible to infer from their rapid adjustment of values that they perhaps thought that the task of achieving the 90-degree turn is closely within their reach and the tinkering approach offered a quick reward. Debating strategies would have asked for deferment of that reward. An instructor could argue that this extended tinkering episode was unproductive for Coral and Bianca toward the goal of helping students produce robust solutions to the design task of maze-navigation.

Yet, there are other instructional goals toward which we see their actions as productive. This episode of tinkering also shows Coral and Bianca engaging in good design practices. Coral and Bianca start by identifying a subtask within a more complex task and proceed to solve that first [139]. In pursuing this subtask, they engage in multiple strategies, without getting fixated [140] and switching tactics when one didn't seem to produce desired results. They test their ideas frequently, at times judiciously focusing on strategy rather than on the detail. For example, while working on the subgoal, they start their delay by using placeholder values, to see if their code generally does what they want it to. In some sense, the initial testing of the delay function is a rapid prototyping move [109] that can confirm or dispute their hunch that introducing a delay would help them accomplish their goals, before spending additional time discussing what value the delay should have. And, consistent with goals of rapid prototyping, they learn more about the system and introduce modifications (making it move forward after every turn) before moving on to fine-tuning their code. This kind of goal adaptation frames their initially non-working code as a building block, rather than a mistake. They also try reducing error by taking into account physical features of the system (moving the USB cord, checking for hardware connections to the Arduino, making sure the batteries are connected and switched on, etc), reflecting an understanding of how the system behavior is emergent from a complex set of couplings between the physical system, the microprocessor, and the software. This simultaneous attention to hardware and software reflects a form of expertise in the design of embedded microprocessor systems [141].

And at every step, they had to make judgments for the next steps. Thus, the episode we label as tinkering was productive toward the engagement of Coral and Bianca in authentic design practices. Imagining alternatives, it is possible that if they engaged in carefully scaffolded and planned activity from the start, they might have spent less time on this task, but missed out on the experience of employing a diversity of practices and taking chances and making judgments of how to proceed in a way that seems productive. Judgments of productivity toward goal is also a skill that expert designers need to hone [142].

This tension in labeling the episode as productive or unproductive illustrates how it is important to consider the grain-size of activity when evaluating productiveness. On a finer grain size, Coral and Bianca engaged in authentic design practices that helped them make progress toward their goal of making the Arduino-bot turn (and to navigate the maze in the back of the classroom). With respect to the role of the learning environment in providing opportunities to engage in the practices of design, one could see this episode as being productive. Zooming out to a larger grain-size, we see that the overall strategy of open-loop programming was unproductive toward developing a robust solution. Depending on how one prioritizes the instructional goal of experiencing design practices in relation to the goal of developing a robust solution, one would end up arguing differently about the productivity of the students' actions captured in this episode.

To be clear, we don't want to suggest that these two instructional goals are mutually exclusive: instructors can strive for both simultaneously, and students can pursue both simultaneously. We can imagine scenarios where tinkering might not satisfy either goal and scenarios where students' action trajectories lead them to satisfy both. It just happens that the trajectory of Coral and Bianca in this episode helps us (researchers) illustrate this grain-size dependence of judgments about the productivity of students' design actions.

3.5.3 Coral: Valuing Tinkering for Affective Engagement

So far, we have discussed how tinkering can be productive toward some goals in some situations: it can support students in more deliberate sensemaking, making progress toward their design goals, and engaging in authentic design practices. At the same time, the lack of extended reflections in the decision-making that characterizes tinkering can also be unproductive toward developing a robust solution, and in some cases completing a design task. Here our arguments for what is productive (or not) relied mostly on the instructors' or educators' perspective. We now turn to how students might affectively experience tinkering as another lens through which to consider productivity.

As described in the data collection section, we also conducted interviews with students to explore how they experienced the design activities. Here, we draw on an interview with Coral which occurred at the start of the second week of camp. At the time of the interview, Coral and Bianca had just begun their final project. In her interview, Coral discussed the nature of design, and how design requires frequent testing of different solutions. What stuck out to us was Coral's articulation of how tinkering mediated her emotions during and about design. In the segment transcribed below, Coral discusses the challenge (and associated emotions) of coordinating the motion of Arduino-bots, one for each of the baby's (robot) feet.

> Interviewer: How are you ensuring that the two robots will work together?
> Coral: So, we do have two programs for the two. but we know that from today we saw that one seemed to be moving a little bit faster than the other. So we were thinking of trying it just at a lower motor speed or possibly changing out the batteries of the one that was moving slower since we have been using those a lot and the other ones were like new batteries. So we thought about that and then also, just testing, a lot a lot of testing. and like slightly altering the program here but not too much where it'll make a drastic change and you have to alter the other one and yeah.
> Interviewer: So like, making little changes, seeing how it works, making a little more changes, seeing how it works.
> Coral: Yeah. and just like, not getting frustrated, being like, this is going to be difficult to move the two and we both understand that, so it's just fun and go from there.

Though Coral doesn't explicitly say "tinkering," her description of testing aligns with how we have been describing tinkering. Coral discussed a design problem in which the motors weren't *a priori* matched in speed. She then describes anticipating multiple courses of potential action and subsequent fine-tuning of the parameters in the code via testing. Coral describes "not getting frustrated" as an important component of doing this work. She elaborates more on frustration in the subsequent conversation:

> Interviewer: What happens when things aren't working? You're feeling frustrated?
> Coral: I think it's definitely like, you're going to get frustrated and I've done enough with robotics to know that it's a frustrating task sometimes. But you just have to kinda know that like, if I don't change it, it's not going to change, and if you want that end goal, or if you want it to accomplish what you want it to accomplish, it's just gonna take time.

> And testing different things, trying out different values, different codes maybe, different ideas, taking a second to like, just leave it and then just letting your mind play around with different ideas and just stepping away from the project for a second, and coming back to it. So, I mean, I think it's one of those things where, I do get frustrated but I don't think it's overwhelming where I ever really feel like "Okay, that's it, I'm done."

Here we see a little more of what that testing process looks like for Coral. "Testing different things, trying out different values, different codes maybe, different ideas," reflects using multiple strategies to achieve a result. To Coral, this process is not only helpful, she sees it as an integral part of doing design. She pairs productive frustration with this testing process and accepts it as part of the design process and of achieving design goals. Her utterance also suggests that this process helps her maintain positive affect. Part of this affective modulation relies on knowing that things will take time; but it's also supported by having multiple ideas to draw on (if one does not work, they can switch to a different idea), of having the freedom to take a break and then revisit the task with fresh ideas. In this way, tinkering prevents her from getting debilitatingly frustrated when things don't immediately work out as planned. There is an epistemic nature to her affect (similar to what Jaber and Hammer call "epistemic affect" [129]), in that she considers frustration as naturally associated with design activities and her epistemological orientation of tinkering being an valid practice within design helps her in mediating that frustration and keeping it "just fun."

3.6 Discussion and Implications

Though tinkering may not necessarily lead to generalizable content learning, it can be productive toward multiple goals for a design classroom. This work sheds light on how tinkering emerges in the design process, discusses cases to illustrate how tinkering can be simultaneously productive toward some goals of an engineering design learning environment and unproductive toward others, and how tinkering might impact student engagement. We conclude this paper with some recommendations for researchers and instructors, as well as a reflective comment on our role as researchers of design practices.

3.6.1 The importance of a broad sense of "productivity"

This paper emphasizes that it is not enough to argue whether something in a classroom is productive or unproductive. We must specify the ends toward which something is productive or unproductive, and acknowledge that the same activity may be productive toward some ends while being unproductive toward others. Within a classroom, students' goals might differ from instructors' goals, each participant might hold simultaneous goals (that might be in tension), and participants' goals may change over time. It is important to articulate these goals before assessing whether an activity is productive.

Tinkering was productive toward Hazel and Silver's extended engagement in authentic design practices. While tinkering, they utilized resources without getting too bogged down in one strategy, used multiple iterations to build specific knowledge about the system, and drew connections across tasks. Tinkering also helped them identify aspects of code that they did not understand, on which they later did more systematic analysis. We argue that in some cases, tinkering can be productive toward supporting students in the systematic unpacking of concepts.

We use the example of Coral and Bianca to illustrate how whether or not one considers an activity to be productive depends on one's goals (asking, productive toward *what*). Tinkering supported Coral's and Bianca's engagement in an open-loop control strategy, which was overall unproductive toward completing their design task. They still engaged in many authentic practices while tinkering. For example, they adjusted the goal based on the system, used placeholder values, and revisited the problem in the process of designing a solution. Interview data with Coral also pairs tinkering with positive affect related to lowered frustration, and some acceptance of frustration as being part of the tinkering process. While tinkering was unproductive toward developing a robust solution, it was productive toward engaging students in design tasks and supporting positive affect.

3.6.2 Whether and how one intervenes also depends on one's goals

This goal-dependent analysis of the productivity of tinkering in an engineering design learning environment also points to the tensions in instructional choices.

The example of Coral and Bianca is useful for thinking about how one's goals might lead to different kinds of interventions. If one valued students completing the specific assigned design task via the most efficient path, one might steer students toward the more successful or more sophisticated strategy (such as a sensor-based closed-loop control strategy in the case of Coral and Bianca). While we can envision that working out well, we can also envision situations in which such an intervention might lead students down the path of just doing what the instructor tells them to do, rather than engaging in authentic disciplinary practices. On the other hand, an instructor who values students' engagement in reflective design alongside developing robust solutions could intervene to have a discussion with Coral and Bianca, asking them to consider a broader set of strategies to solve the maze-navigation task and about the relative robustness of solutions. This might prompt students to engage in more metacognitive reflection about their activities. Another valid instructional choice could be to not intervene. An instructor could decide that Coral's and Bianca's engagement in the design practices is valuable in itself, irrespective of whether their broader strategy works or fails. The success or failure of their final design can be utilized for further reflection later, without needing to redirect them during the process. In each case, instructional choices are guided by how we interpret what we see students doing, how we imagine their projected trajectories through the design project, our goals for what we expect students to achieve in the process, and our judgments about whether the projected trajectories align with those goals.

The case of Hazel and Silver also illustrates that sometimes, an activity may be productive toward supporting an instructional goal at a later point in time. Though Hazel and Silver did not engage in systematic sensemaking (specifically, parsing and making sense of the code) when starting the task, tinkering did support them in deliberate sensemaking about the code later by helping them identify relevant pieces of the code they needed to understand. Thus, even if an activity is not supporting a certain goal in the moment, it could still be useful for an instructor to hold back instead of intervening. That some activities may support more conceptual learning at a later point in time has also been discussed in science education [120, 143].

3.6.3 Equity implications of privileging some practices over others

We also find it valuable to reflect on one's goals in a classroom because it is important to question why we value some goals over others. Many instructors have valued students learning engineering concepts, developing robust solutions [144], and engaging in some disciplinary practices. When instructors choose to privilege these goals over others, and thus value some kinds of participation over others, it has consequences for students' long-term ability to participate in design. As prior research has shown, not every student has access to (or chooses to engage in) the celebrated practices and goals within an engineering classroom [37, 39, 83]. These differences can lead to the marginalization and attrition of many students who have the capacity to succeed in engineering. Given how some research has suggested that practices such as tinkering may be gendered [39, 85], discouraging tinkering may also lead to an inequitable learning environment.

It is important to consider how what we value may disproportionately marginalize students. We encourage our fellow designers and instructors to critically reflect on the questions of what counts as good engineering in our classrooms and why we consider some activities to be qualities of better engineering than others. If we privilege certain activities because they are aligned with what has historically been valued in engineering, we may continue to make engineering available to only a limited set of students. Instead, we would like instructors to consider how an engineering classroom may value a plurality of approaches and engagements in engineering. Bringing a broader set of engineering classroom goals to the fore is an important step in making our classrooms and institutions more inclusive.

To summarize, we argue that students' tinkering behaviors can have a productive role in the engineering design classroom but productivity must be evaluated in the context of one's goals. Other work in science education has argued for the importance of taking these goals into account when we call something "productive" or "unproductive" (e.g. [123, 128, 129]). We argue that there are many legitimate goals that instructor might have in a design classroom and it is useful to ask *in what ways* tinkering is productive or unproductive. We presented several cases of tinkering and not tinkering to refine our sense of what tinkering is and in what ways tinkering is productive.

Chapter 4: Interactions between disciplinary practices and joint work in undergraduate physics research experiences

4.1 Abstract

We analyze how participating in undergraduate research experiences (UREs) influenced physics students' trajectories of participation within the community of practice of physics researchers. Students in the study participated in an elective seminar in which they were paired with graduate student and faculty mentors on physics research projects and participated in weekly discussions about research. Using video data from student interviews and mentor interviews, we characterize two aspects of students' engagement in the physics community of practice. First, we find variations in their engagement in authentic physics practices, which we characterize as physics activities which are connected and purposeful. Second, we characterize forms of joint work by the research project's form and structure and by patterns of interaction between undergraduates and mentors. We argue that forms of joint work influenced students' varied senses of how physics activities are connected and purposeful. Finally, we use this understanding to suggest how to better scaffold UREs to enable more authentic participation.

4.2 Introduction

Far too often, STEM classrooms are harsh educational systems that weed out students who have the potential to be great scientists. Introductory "gatekeeping" math and science courses often invoke the mentality that their purpose is to cull the top students and filter out the rest [5, 145]. STEM classrooms are rife with elitist attitudes and competitiveness aligned with the socialization of white men [5]. These systems disproportionately impact women and students of color and this leads to the attrition of many students, even students who are able to achieve good grades and be successful in coursework [5, 8]. Given that students are not afforded equitable learning opportunities within university structures, this motivates work toward understanding the interactions and settings in which disciplinary learning occurs, where "learning" encompasses increasing participation in the physics community, not just particular conceptual and procedural understandings. We seek to understand how the structure and forms of interactions within settings impact what is learned and who can learn in them. This will support us in understanding how to foster a diversity of successful pathways into STEM.

One way to foster such pathways is through undergraduate research experiences (UREs). Physics as a field often emphasizes the value of UREs [146], describing them as "authentic" and "real" science in relation to standard coursework [10]. Moreover, UREs increase retention in STEM fields, particularly for students from underrepresented backgrounds [10]. But research shows that UREs are not accessible to all students. UREs are often acquired through informal means and many students have limited knowledge of what UREs entail and what opportunities exist [147]. This suggests that developing programs which lower the barrier to participating in UREs, and making them available in the crucial early stages of students' academic trajectories (when many students consider leaving physics), could enable a broad set of students to access the benefits of UREs.

We developed a seminar at the University of Maryland, College Park with the intention of fostering new pathways into physics through giving students the opportunity to participate in research experiences. Any student who was interested in research but was not currently doing research was encouraged to enroll during advising. This course is part of the Focus on Physics program in the Maryland Physics Department, which is one of eight inclusiveness-focused programs in the Access Network. The design of the seminar aligned with core values of the Access Network, including adopting a "whole person" approach [11, 148] which involves community building and explicitly discussing students' struggles and senses of identity as they connected to physics. The seminar was paired with ongoing research with outside mentors, giving students the opportunity to participate in more authentic activities than is often found in traditional coursework. Through these activities, we hoped to 1) expand the set of pathways toward becoming a scientist by refining students' understanding of what science is and 2) support students in seeing themselves along such pathways.

Our research on this setting studies how the seminar and research experiences afforded shifts in students' participation in physics. Our approach integrated several dimensions of students' participation—shifts in their knowledge of physics and physics research, shifts in their abilities and skills, and shifts in how they saw themselves and were recognized by others as doers of physics. This paper focuses on one thread of this work, looking at whether students came to participate in authentic physics practices. We define authentic physics practices as physics activities that are connected to one another and to a scientific purpose. We then studied how that was impacted by joint work with their research mentors. We found that the forms of joint work impacted the extent to which students experienced the connectedness and purposefulness of scientific activities.

4.3 Background

Prior research on undergraduate research experiences (UREs) suggests that UREs can have numerous positive outcomes, including development of content knowledge, research skills, productive beliefs about physics, and disciplinary identities [81, 149–152]. Research experiences can also support students' persistence in STEM fields [10, 153, 154]. This work informs a wide set of national recommendations to increase the number of students participating in UREs [10, 155].

Much of this work has identified and categorized the specific scientific activities in which students engage. A study by Hunter et al. describes student gains from doing research [149, 156]. Their category *Gains in understanding science research through hands-on experience* includes items such as problem solving, analyzing, and interpreting results and *Gains in Communication skills* includes items such as presentations, writing, and laboratory/field techniques. Similarly, the Undergraduate Research Questionnaire [150, 157] subscale *Research Methods* probes for whether or not students engage in individual research activities:

> I can design experiments
> I can troubleshoot experiments
> I understand how to report experimental results.
> Generating hypotheses is something I can do.
> Data analysis is something I can do.
> Carrying out experiments is something I can do.

This body of work illustrates the breadth of activities that students in UREs engage in. These activities often differ from those found in traditional lab courses [158].

Other research on UREs has discussed the relationship between mentoring and student outcomes. Mentors who spend more time with the mentee, are enthusiastic and engaging, and make themselves more available tend to be associated with greater learning gains and identity development [150, 156, 159]. Byars-Winston et al. found that specific mentoring activities such as giving constructive feedback, and helping mentees place their research in terms of a larger project impacted students' self-efficacy [160]. Other quantitative research has found small but statistically significant correlations between students' learning outcomes and mentorship characteristics (e.g., perceived quality); these authors argue that the weakness of the correlation is due to the complexity of mentoring relationships, and they recommend further study on the impact of research mentors [151, 161].

In summary, prior research has insightfully identified many positive outcomes of UREs, including naming the scientific skills students develop and activities students engage in, and has started to identify consequential features of mentoring relationships that lead to positive outcomes. However, we argue that much of the work on UREs treats scientific activities in reductionist ways by quantifying isolated skill-based outcomes and characterizing experiences as more positive when students engage in more of these activities [81, 150, 151, 156]. These items do not capture students' understandings of why these activities are important to science or their relationship to other scientific activities. For example, consider the URQ item:

> I understand how to report experimental results.

We agree that presenting and reporting on experimental results is an important aspect of science, and at a coarse-grained level, it can be important to know how many students engage in this activity. However, we see the presentation of scientific results as meaningful because of how presentations function in the scientific community toward the refinement of scientific ideas. This item also does not assess whether students are able to judge the appropriateness of such a presentation or see how that activity is meaningfully connected to the other activities that led to the presentation.

Instead of looking at doing science as a set of skills and activities, we argue for a focus on scientific *practices*. Practices are sets of activities that are embedded within and work toward the aims the scientific community [63]. So, from the student's perspective, a "skill" or "activity" becomes a practice to the extent that the student sees the "point" of the skill/activity, how it meshes with other skills/activities and with the broader purpose of the research group's work. Studying practices takes into account how these activities interact with one another and serve a scientific purpose. We do this for two reasons: 1) The intuitive sense that doing science is more than just the enactment of certain kinds of knowledge and skills; engaging in science also relies on seeing how each component is meaningfully connected and embedded within a broader scientific purpose, and 2) Our commitment to viewing learning as a process of legitimate peripheral participation [41,59], in which learning is not reducible to the accumulation of specific skills and knowledge.

We start by asking, *what does it look like for newcomers in physics research to come to engage in authentic scientific practices?* We foreground two aspects of participation that Lave and Wenger highlight as important aspects of participation in all communities of practice [59]: (i) engagement in the community's practices (in this case, scientific practices), and (ii) the joint work between less experienced and more experienced community members (in this case, students and mentors). To study engagement in scientific practices, we use a framework from Ford [64] which defines practices as activities which are *connected* to one another and to a *scientific purpose*. To study *joint work*, we look at the *form and structure of the research projects*, as well as the *patterns of interaction* between mentors and students. We argue that the forms of joint work impacted students' senses of connectedness and purposefulness. In our discussion, we use this understanding to suggest how to better scaffold UREs to enable more authentic participation.

4.4 Theoretical Perspective

In this section, we discuss our theoretical perspective for this work. We first discuss viewing learning as a process of *legitimate peripheral participation* within a *community of practice*. Because this framework has been used to conceptualize learning in many kinds of communities, we elaborate on our conceptualization of the discipline-specific aspects of the physics community of practice. To do this, we use a framework from Ford to conceptualize authentic engagement in physics practices, which is defined by scientific activities that are meaningfully connected to one another and to a scientific purpose.

4.4.1 Legitimate Peripheral Participation

As conceptualized by Lave and Wenger, situated learning theory describes learning as the process of shifting participation within a community of practice [59]. A community of practice is a set of people who work together on shared activities toward a set of shared goals. Wenger refers these shared goals as the community's "joint enterprise" [41]. Within a community of practice, legitimate peripheral participation (LPP) refers to the process of novices learning through engaging in joint work with experts [59]. Depending on the form and structure of these activities, they can facilitate deeper understanding of the community and engagement in more central practices of the community. Membership within the community is complex; there are a diversity of ways to participate, and similarly a diversity of ways that participation shifts. The processes of learning and identity development are directly intertwined with one's shifting participation.

The process of shifting participation within a community of practice is neither a linear, nor smooth process. Interactions with other members of the community can lead to participating in more central practices, or cordoning off access to central practices. Who one is and how one engages in disciplinary practices is dependent on the form and nature of the joint activities and interactions with others. This perspective has been used by other scholars in PER and science education to describe how learning is impacted by contextual features of learning settings, such as aspects of a student community and classroom supports and structures [162–165].

Within our work, we conceptualize the physics research community as a community of practice. A central goal of the physics research community is to advance the understanding of nature through creating coherent causal explanations of physical phenomena. The community itself is broad and distributed. Roles and responsibilities vary across subfields, research groups, and within research groups. Moreover, within subdisciplines of physics, the kinds of epistemic approaches and commitments vary [54]. Meaning, the use of different research approaches, and the logic guiding how those connect to scientific knowledge differ in subfields. Therefore, we expect differences in each student's trajectory in the physics research community depending on their subfield, project, and interactions with other members of the community. For example, a research experience in a large collaboration would differ from a research experience using tabletop experiments, in terms of division of labor and which scientific practices are prominent. Even the enactment of the same scientific practices, such as engaging in critique or crafting a scientific publication, would look different in the two settings.

Literature from interaction analysis informs our perspective on characterizing joint work in UREs. Barron described multiple forms of joint work enacted by children solving math problems, taking into account students' social interactions and disciplinary engagement [166, 167]. Barron identified several dimensions of coordination in groups: *Shared Task Alignment* (a "collaborative orientation to problem solving" which includes building off of one another's ideas), *Joint attention* (such as toward a workbook or other problem solving artifact) and *Mutuality* (the potential for all members to contribute). While this research focused on children's problem solving, we find that this work gives us a language for describing forms of engagement in research groups. Some forms of research group participation might look like what Barron calls *coordinated co-construction* (characterized by shared task alignment, joint attention, and mutuality) where students meaningfully contribute ideas in dialogue with mentors on a joint task. A research project in which a mentor delegates tasks, and the mentee works with little monitoring or feedback would have little shared task alignment or joint attention. While our data about each participant's engagement in joint work in their lab comes from interviews with participants, we find that Barron's characterizations of joint work help us articulate differences in patterns of interaction across research groups. We elaborate on this in our Analytical Approach in Section 4.5.

We now turn to prior work on authentic disciplinary practices to describe how we are analyzing practices in this paper.

4.4.2 Authentic Disciplinary Practices

We conceptualize scientific practices as activities that are embedded within and work toward the aims the scientific community [63]. Practices are also logically coherent with respect to other practices (Berland et al. refer to the set of practices as an "ensemble of activity." [65]) For example, the activity of running an experiment is considered a practice if the experiment is connected to a driving question about a phenomenon and to a sensible method of analyzing the data such that disciplinary knowledge could be developed. It would not be considered a practice if it was done as an isolated activity, independent of the underlying logic of how the experiment would produce scientific knowledge. Thus, the extent to which an activity is a practice is dependent on how it is embedded within the ensemble of activities and goals of the community.

We apply a framework from Ford [64] who draws on work by Rouse [66] to describe authentic scientific practices from a holistic perspective. Ford conceptualizes practices using the Next Generation Science Standards (NGSS). While the NGSS outlines several practices for K-12 (e.g., modeling, formulating questions), Ford foregrounds that its purpose is not to enumerate individual practices but rather to draw attention to how they function in relation to one another and to the broader scientific enterprise [40]. He describes three key features of practices:

1. *Connectedness*: The performances of a practice interact with one another in a meaningful way, and that there is some way to judge the appropriateness of the performance.
2. *Purposefulness*: The performance is evaluated and critiqued within a purpose —within science, this purpose is its ability to "explain nature." (cf. [65])
3. *Prospectiveness*: Practices are prospective or forward thinking, which captures how our scientific tools and approaches evolve over time.

Within this paper, we omit the third feature, both for brevity and because we did not have as much evidence of it in our data.

This framework provides a language for us to describe the extent to which scientific activities are *practices*, based on whether students are able to understand and articulate the connectedness and purposefulness of those activities. Ford frames these features of practices as idealized end-goals for scientific engagement, and challenges researchers and practitioners to think about how one scaffolds early engagement in practices. Taking up this challenge, we apply this framework to early UREs to understand forms of legitimate peripheral participation in scientific practices, and consider how those forms of legitimate peripheral participation emerge through different forms of joint work.

4.5 Analytical Approach

4.5.1 Classroom Context

This study is embedded within a larger multi-year study of first-year physics majors' first undergraduate research experiences. Students in the study enrolled in *Physics 299B: The Physics Toolbox*, a course at the University of Maryland. This course was co-developed by the first author and another instructor in 2013 and has run yearly since then. In this paper, we focus on data from one focal semester of Physics 299B that was not taught by any of the authors. In this focal year, Quan met regularly with the instructor to brainstorm classroom ideas and talk about how the class was going. All first-year physics majors who were not currently engaged in research were encouraged to enroll during advising. The course typically enrolls fifteen to twenty students (the physics department typically has about 50-60 first-year freshmen and transfer students per year). In our focal year, five (31%) students identified as female and eleven (69%) students identified as male. Ten students (63%) identified as white or Caucasian, three students (19%) identified as Asian, two students (13%) identified as African-American, one student (6%) identified as Hispanic, and one student (6%) identified as Middle-Eastern (students could self-report more than one demographic category).

There are two components to the course: 1) Working in pairs with graduate student and faculty mentors on research projects outside of class and 2) participating in a weekly seminar, with a separate instructor, where they developed research skills and reflected on their experiences. Instructors recruited mentors (faculty, post-docs, and advanced graduate students) whom they felt would create meaningful learning opportunities in their research labs. Mentors proposed projects of reasonable complexity for a first-year undergraduate to complete in one semester. Students were matched with mentors based on topical interest. For 3–5 hours per week over twelve weeks, students worked with their mentors on research projects.

Research projects spanned experimental and theoretical physics and astronomy. One focal student in this paper, "Frank," worked on a theoretical plasma physics project with a postdoctoral researcher. Another focal student in this paper, Neil, worked on an experimental atomic and molecular optics (AMO) project with a graduate student mentor. Cassandra worked with a professor on a theoretical cosmology project. Each mentor was given a set of mentor guidelines which outlined the expectations for time commitment, made recommendations for bounding an appropriate-sized project within the time constraints, and listed topics covered in the 299B course. Mentors were carefully recruited and were given few guidelines over which aspects of the physics research to emphasize to students. We did not communicate any of the central themes presented in this paper, such as connectedness and purposefulness of practices, to mentors as potential topics of discussion.

In addition to working on research projects, students met for two hours per week in the 299B seminar. Course goals and structures were informed by Quan's participation in the Compass Project at the University of California, Berkeley [1] [11, 148, 168]. Two central goals guided design of the course: (i) developing a supportive community that shares the ups and downs of doing research, and (ii) giving students opportunities to reflect on and be proud of their work [169]. As a result, much of the seminar consisted of small-group and whole-class reflections on students' research activities. The seminar also included open-ended activities for students to learn and reflect on research skills applicable to most research projects, such as reading literature and conducting error analysis. The course culminated in a poster session open to all members of the physics department.

Class discussions did not explicitly discuss connectedness and purposefulness. However, it is likely that class activities supported students in seeing scientific activities as connected and purposeful. For example, one course activity involved constructing an "elevator pitch," or a short verbal summary of your research for someone not in your field of study. Students also drafted and gave each other feedback on their scientific posters. In both of these activities, students were encouraged to articulate the main point of their work, which likely encouraged them to consider the flow of activities and how they supported a scientific purpose.

4.5.2 Data Collection

The purpose of this data collection was to understand how students shifted participation within a physics community of practice. When we began data collection, *connectedness* and *purposefulness* had not emerged yet as themes for analysis. In the focal semester, Quan collected classroom videotapes, observations of students in their labs, and interviews with students and mentors. Because our analysis was focused on identifying shifts over time, we conducted pre- and post- interviews. All pre-interviews were collected before students had started research projects, except for Cassandra's interview, which was conducted four weeks into the research projects. Because we expected to identify participation via how students were positioned by others or positioned themselves as more or less expert-like, we also interviewed mentors and observed research lab interactions.

All 17 students were invited to participate in classroom data collection and pre-/post- interviews. We collected six pre-interviews and eight post-interviews (five students participated in both). Interviews were semi-structured [170] and topics in-

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[1] The Compass Project is a student-led program dedicated to improving equity in the physical sciences through several activities, including courses and a summer program for first-year undergraduate students. The Compass Project is one of eight institutions in the Access Network.

	Pre	Post	1-Year	Mentor Int
Frank	X	X	X	X
Neil	X		X	X
Cassandra	X (mid)	X	X	

Table 4.1: Summary of data streams for each of the three case studies featured in this paper.

cluded students' attitudes toward their research project, students' sense of belonging within the physics major, and what they felt like they were getting out of doing research. In post-interviews, the interviewer also followed up with students on themes discussed in the first interview.

For the six students who completed pre-interviews, we invited all five of their mentors to participate in interviews mid-semester. Four mentors participated. Mentor interview questions asked them to describe their research projects, how they thought students were doing in the project, and what their goals were. After collecting mentor interviews, Quan invited the four mentors who had been interviewed and their mentees in those groups to participate in research observations. Quan conducted three research observations. Three focal students were invited to participate in interviews one year after the course ended. We elaborate on the selection of these case studies at the end of this section.

4.5.3 Analysis

After the first round of pre-interviews was collected, Quan developed content logs [134] which noted the main themes of each interview. We were initially interested in how students did or did not have access to physics practices, so we flagged moments in which students and mentors positioned students relative to the activities of the discipline. Throughout this process, several themes emerged such as how activities were contextualized within the broader field of physics, and the ways in which students were invited to participate in these practices. During this process, we moved between our emergent categories and themes in the literature, including students' senses of connectedness and purposefulness of the activities in which they were engaging. After refining categories, we fully transcribed the interviews and flagged moments in which students or mentors described their lab-related activities as being connected (or not) to one another or purposeful (or not). We labeled activities that were connected and purposeful, "practices."

We then developed analytic memos in which we used transcript segments to develop claims about how features of the project and working relationships supported connectedness and purposefulness [13, 134]. We refined our analyses by synthesizing our accounts of students and mentors on the same mentor-mentee research teams [20, 136]. In all cases, students' and mentors' gave well-aligned descriptions of central features of the project and of their working relationship.

Ford's paper is theoretical and foregrounds features of scientific practices over how students engage in those practices. Therefore, we had to link Ford's features to what can be inferred from interview data. As researchers, we believe our interpretations of students' engagement in connectedness and purposefulness using interview data is but one facet of their engagement in scientific activities. Analyses drawing on *in situ* data would illuminate complementary facets worth exploring [20].

We inferred connectedness when students described several activities as following one another sequentially, when the latter activities plausibly built on the earlier ones (e.g., "we learned theory of circuits, then we played with circuit parts"). Stronger evidence involved students more explicitly describing one practice as stemming or building off of one another (e.g., "we implemented code based on the theory we had learned before"). We identified purposefulness in statements in which students described how their research was motivated by or supported the generation of scientific knowledge. This included instances when a student framed their work in terms of an unanswered scientific question or articulated what scientific knowledge was gained from their work. In some instances, students articulated that they did not know how their work would benefit the scientific community, which we took as evidence of lack of purposefulness. We also noted instances in which students found their work personally meaningful or purposeful toward other goals—e.g., a student saying his project was meaningful because he enjoys feeling like he helps others—but we chose not to include those in this paper, partly because this is a different sense of purposefulness than the one in Ford's framework.

Our theoretical perspective and early analyses informed which aspects of joint work we chose to focus on. As noted above, Lave and Wenger suggest that shared activities and relationships between members impact engagement in the activities of a community of practice [59]. In trying to understand mechanisms driving connectedness and purposefulness, we similarly noticed that students described several aspects of working relationships and interpersonal dynamics as being consequential. We then developed analytical memos noting how these aspects seemed to impact students' engagement in activities. Using Spradley's approach to ethnographic analysis, we constructed categories of joint work that came up as relevant (e.g., "responsiveness to concerns" and "flow of activities.") [171, 172]. We then looked for and studied each of these categories within the broader set of data. Incorporating more data, including mentor interviews, helped us expand and collapse categories, and then we repeated our analysis. By iteratively refining our categories and looking across more data [136], we identified two main grain sizes of joint work to focus on, *project form and structure*, and *patterns of interaction*. Throughout this process, some features of joint work stood out as salient only once they could be seen in relief of the broader data set. For example, a student describing a research mentor as "always available" became more meaningful when another student described interactions with a different mentor as "sparse." These analyses and video data were also presented at research group meetings to identify the claims that were best supported by the data [134].

In the next section, we discuss the affordances and drawbacks of relying on interview data to discuss engagement in activities and patterns of interaction in labs.

4.5.3.1 Using interviews to infer patterns of interaction and students' engagement

Historically, interviews have been used to infer students' perceptions and abilities whereas observations and video analysis are more commonly used to study engagement. But within our analyses, we use interview data to make claims about engagement outside the interview setting, drawing on literature and constructs that were primarily developed using *in situ* data collection. We now discuss the affordances and drawbacks of using interviews to study engagement in activities and patterns of interaction.

We identified students' senses of engagement in interview questions prompting students to describe what it was like to do research in their labs, such as "Can you tell me about your research in 299B?", "What was your relationship with your research mentor(s) like?" and "What would a typical day in research have looked like?" These questions give us access to aspects of what students are doing and thinking that may not have been verbalized within mentor-mentee interactions. We also gain access to features of interactions that are most salient to participants; because our ultimate goal is to understand students' long-term participation in physics, we find their "truth" about these interactions to be especially relevant.

Interviews also give insight into flow of activities without watching them the whole time within the research experience. Given the time required to collect and analyze observational data, it may not be feasible to develop analyses about the flow of activities in several research groups through observation [173]. Finally, the aspects of interaction that we choose to foreground here, descriptions of joint work including which actors are present and those actors' roles within joint activities, is more likely to be reliably reported compared to accounts of the fine-grained details of a conversation. The alignment of students' and mentors' depictions of joint work structures and roles gives us further confidence that those depictions capture aspects of lab interactions.

Had we been more interested in students' performance-based skills or effectiveness at doing research, conducting interaction analysis on *in situ* data would be a better approach. We emphasize, however, that although we might have intuitions that video recordings might have more objective views into patterns of interactions, this viewpoint can harmfully obscure researchers' subjectivity and theoretical commitments [174, 175].

We used other data sources to strengthen our analyses. Quan attended and videotaped every meeting of the 299B seminar, which provided space for students to share detailed descriptions of research experiences and problem solve about their projects. Quan also conducted one research-lab observation of Neil, his partner, and his mentor, and one research-lab observation of Frank's partner and mentor (with Frank absent that day). In both classroom and research settings, Quan was not a passive observer; she asked clarifying questions, contributed to discussions occasionally, and informally talked with students about their academic and personal lives. These observations contributed to greater shared meaning during the interview conversation and our interpretations of students' descriptions [77]. When available, we analyzed research mentor interviews, and interviews with research partners to triangulate these accounts.

An important next step to this work would be to analyze *in situ* research observations to better articulate joint work and understand how connectedness and purposefulness is supported in moment-to-moment interactions. Our interview-based analyses in this paper give insight to where one might focus attention in such analyses.

4.5.3.2 Moving between grain-sizes of participation in disciplinary communities

Wenger [41] and Brown and Campione [52] motivate us to look at participation in disciplinary communities at both broad and narrow grain sizes. We consider the broad grain size to be *project form and structure*, the larger scope of an investigation and flow of activities, whereas *patterns of interaction* happen at a more day-to-day timescale.

Wenger describes the activities of medical claims processors at both the broad project form and structure level and the narrow patterns-of-interaction level [41]. At the project form and structure level, the arc of a processor's role is to receive claims, process them in spreadsheets given by the company, and check their work. At the finer-grained level, several patterns of interaction support this broader structure. New members rely on old-timers for feedback in developing a "feel" for appropriate spreadsheet outputs. Discussions with and observations of old-timers also help enculturate new members into norms regarding day-to-day activities such as phone calls and birthday celebrations. In Wenger's description, both of these grain sizes of activities impact and reflect claims processors' roles in the community.

In a different vein, Brown and Campione describe their *Fostering Communities of Learners* classroom as a broad system where reflection and disciplinary content support research, information sharing, and engagement in a consequential task [52]. At a smaller grain size, they also describe regular patterns of interaction that support this system, such as distributing expertise across group members and conversational norms around epistemic engagement (e.g., providing warrants and backings for scientific claims).

Within our work, we consider these two grain sizes of joint work that emerged as consequential for how students engaged in disciplinary activities. These two grain sizes first emerged empirically, but we found that they matched up to similar grain sizes that other researchers had used.

Project form and structure—This grain size focuses on what the driving questions are, the scope of the investigation, and the overall flow of the joint activity. Driving questions are the broader goals of the project and how the project fits into the disciplinary domain. The scope of the investigation includes the boundaries of what is and isn't being researched. The overall flow refers to the sequencing of activities, and the disciplinary logic behind that flow. Underlying the flow is the *epistemic approach* to the project, or how the project has the potential to produce disciplinary knowledge. An example of an epistemic approach would be that an experimental observation should be theoretically verifiable, which justifies why one should look for theoretical models that explain anomalous experimental observations. This structure is negotiated between members of the community and scaffolded by more expert-like members to varying degrees.

Patterns of Interaction—This includes the more day-to-day interactions that occur in research, such as orientation to tasks, spatial arrangement of actors and materials, timing of interactions, and how accessible actors are to one another. We draw on Barron's characterizations of group work to describe patterns of interaction [166, 167]. For example, a co-working relationship might involve students and mentors maintaining joint attention on the same task. Another pattern of interaction involves mentors and students working on different tasks in the same space, with the student asking frequent questions. Similar to Erickson's social participation structure [176], this includes how people act in the setting and who has information. Within patterns of interaction, we were especially attentive to *responsiveness*, noting the manner and timescale that the mentor responded to mentee's concerns, and the processes by which mentees ask questions and receive feedback.

Markers for joint work were mentor or student statements that described aspects of the working patterns and relationships between students and mentors. We specifically focused on descriptions of *project form and structure* (the joint activities, division of labor) and *patterns of interaction* (interactional dynamics such as physical arrangements, spontaneity of interactions, and responsiveness). In other analyses, we attended to more interpersonal qualities of relationship building such as senses of belonging and friendship building. Due to limited space, we will discuss these aspects in future work. Figure 4.1 illustrates the connections between joint work and disciplinary activities that we identified in this paper.

To summarize, our study of legitimate peripheral participation in the physics community of practice foregrounds two aspects of participation: *engagement in scientific practices* and the *joint work* that students and mentors engage in. To study practices we use a framework from Ford in which practices are defined by their *connectedness* and *purposefulness*. To study joint work, we focus on the broad *project form and structure* and the *patterns of interaction* between mentors and mentees. In our analyses, we look for ways in which the joint work affects students' engagement in connected and/or purposeful scientific activities (Figure 4.1).

4.5.4 Case Selection

In this paper, we present analyses of three focal students, Frank, Neil, and Cassandra. These students had high, mixed, and limited senses of connectedness and purposefulness of their projects, respectively. We chose these students to highlight these differences, and differences in joint work patterns. In the cases of Frank and

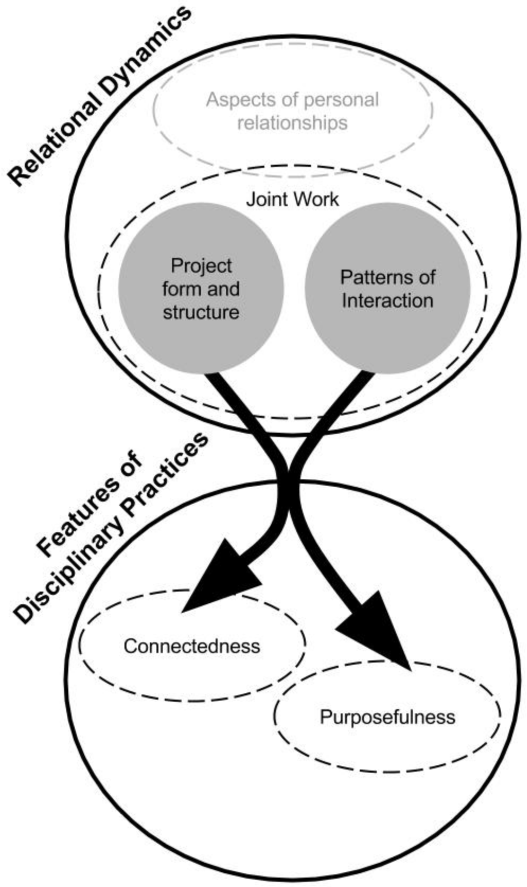

Figure 4.1: Analytical framework in this paper. Project form and structure and patterns of interaction both connect to connectedness and purposefulness.

Neil, we also had data from the student's lab partner and mentor. In the case of Cassandra, we did not have data from either the mentor or partner. Interview data from Cassandra's mentor and partner would have helped us triangulate our claims about the nature of their joint work. We still choose to include Cassandra in this paper because she described the most limited connectedness and purposefulness of any student in the data set, and because her interview data were richly detailed enough to provide insight into why.

Due to limited space, we choose to foreground focal students only. Our purpose is not to reach broad generalizations about how features of joint work affect students' engagement in scientific activities. This is an exploratory study, intended to (i) make plausible our claim that features of joint work affect students' engagement in scientific activities, and (ii) illustrate mechanisms by which these may be connected. We hope this study motivates future qualitative work further charting these mechanisms and quantitative work exploring these connections more systematically.

4.6 Results

For each of the three cases, we first provide a descriptive account of their joint work at two grain sizes: *project form and structure*, and *patterns of interaction.* Next, we describe the *connectedness* and *purposefulness* of the disciplinary activities in which they engaged. Finally, we illustrate how the forms of joint work impacted the degree and nature of the connectedness and purposefulness.

4.7 Frank

Joint work between Frank, his mentor, and his partner consisted of Frank's mentor setting clear learning objectives each week and letting students work on their own or participating in mentor-guided work together. They also engaged in regular periods of joint attention and shared task alignment, while engaging in critique and evaluation of their work. We argue that having well-articulated objectives and opportunities to co-work supported Frank in understanding the connectedness and purposefulness of their activities.

4.7.1 Descriptive accounts of joint work

Frank worked on a computational physics project modeling plasma in the ionosphere. Other researchers had detected radiation in the South Pole and suspected that it had been the same radiation that had been transmitted into the ionosphere in the North Pole. Using ray-tracing in the computer modeling language MATLAB, this project modeled whether it was physically possible for the radiation in the North Pole to scatter through the ionosphere all the way to the South Pole.

4.7.1.1 Project form and structure: A step-by-step approach

Quan interviewed Frank's mentor halfway through the research project. He described planning out the project "from the ground up" and taking a "step-by-step" approach.

> Frank's mentor: ...There are multiple sources that I could have given them, and I could have told them how to do it on MATLAB, and I could have just let them do it...Just kind of like, "hey here's the equations, just turn the crank on the computer." That's not the approach I took...I went step by step, I said "you know, if you want to do this you have to know how to program in MATLAB, how to use MATLAB as a computational tool."...We learned the basics of MATLAB... then actually solving ODEs [ordinary differential equations] on the computer... Then we moved on to theoretical foundations of the equations...at least some background where they come from... to, "hey like, guys, this, what you just learned leads to these equations,"... we'll go back to MATLAB then and we solve the equations on the computer. And that's really when more of

> the research questions are going to be asked. That's when you're like, okay, so what research questions am I asking? And what am I looking for when I'm using the computer? And solving these equations and what output, what do I want to see in my output and finally, what is the output? What are the results? And then that's the progression.

Frank's mentor first describes an alternative mentorship strategy where the mentor tells students how to solve a problem and lets them "turn the crank." He explicitly rejects this approach, in favor of an approach "from the ground up." This approach goes "step by step," starting with learning the basics of MATLAB, then theory, and finally integrating those to answer a research question. In the mentor's interview, he articulates those steps and how they build off of one another. These start from the "ground up," beginning with "basics of MATLAB" and "foundations of the equations" before solving the equations in MATLAB. He connects these solutions to the research questions that drive their work. Frank described a similar flow of activities, which we show in the next section.

4.7.1.2 Patterns of interaction

Frank, his partner, and his mentor met twice per week. When asked to describe a "typical day in research," Frank described several interaction patterns of him, his mentor, and his partner.

> Frank: [Mentor] would explain to us what the objective was for the day. Whether it was basic coding towards the beginning of the sessions or theory of the plasma frequency and the index of refraction. He lays down the groundwork, and then we go in. We start coding exactly what we think should happen... from what we know, and then submit that to [Mentor], he would look it over, and then we confer... Or it would be [Mentor] gives us a code and tells us to play around with it and see what we can do... [My partner] and I then figure out whether our ideas are aligned, whether they're not aligned, what makes sense, what doesn't make sense. And so it would be a group project, where we go back and forth. We all have a third of the project to do. And, we confer and we make it a whole.

Frank stated that his mentor explained their work in terms of daily objectives, suggesting that his mentor supported them in breaking their work down into smaller subgoals. This division into daily objectives aligns with the "step by step" scaffolding as his mentor described above. We interpret Frank's description of going "back and forth" between doing one's part of the project and conferring to "make it a whole" to mean that their work oscillated between working separately and co-coordinated activities.

Frank describes several places where they maintained shared task alignment and joint attention, "he lays down the groundwork," "we confer," and regular evaluation of his work with his partner and his mentor. This was aligned with the working patterns that were observed in our observation of their research team, in which Frank's mentor observed and guided his partner through derivations of differential equations on a whiteboard. According to Frank's mentor, they met for two one-hour meetings per week in a conference room that he had reserved. Frank's mentor described the bulk of their research activities as being done within these in-person meetings, stating "Right now we're going from theoretical foundations to equations...after one or two meetings we're going to immediately move onto the full problem and it will take another meeting or two after that to finish." This description of accomplishing subgoals within meetings, and his use of the word "we" suggests that their joint work in these meetings involved co-coodination of activities.

4.7.2 Engagement in disciplinary activities

Frank's mentor described the scientific activities in terms of how they connected to one another and answered a scientific question. In the above quote from Frank's mentor, he noted many of the activities and how they are connected to one another in a "step-by-step" way. First, students learn how to solve ordinary differential equations in MATLAB. Then they learn "theoretical foundations" so they know where the ODEs they would program came from. Finally, they integrate this theory and programming into solving equations for their system on the computer. At this point, the activities come together toward answering, "What research questions am I asking?"

We found evidence that Frank also experienced connectedness and purposefulness with respect to scientific activities.

4.7.2.1 Engagement in connected activities

In the above quote from Frank, he drew connections between computational and theoretical aspects of his research, as well as how their engagement connected to scientific critique. Within this description, there is evidence that activities are connected for Frank. He outlines several activities such as "laying down the groundwork," enacting computation, and engaging in evaluation of those performances. Frank's use of the transitions "and then" between the activities suggests that they are connected sequentially. The coding processes also directly connect to their conceptual knowledge ("we start coding exactly what we think should happen... from what we know") suggesting that the computational processes stemmed from conceptualizing predictions of what they thought would happen. In the second half of the quote, Frank describes another mode of engagement in which they explore a code that had been previously developed by other researchers. Using this exploration of previously developed code, they figure out "whether our ideas are aligned" with one another's. This critique is connected to the understanding they developed through previous exploration of the code. Frank's description of how scientific activities flow into one another makes sense to us as researchers and helps us understand how Frank is making sense of the logic behind his inquiry.

4.7.2.2 Engagement in purposeful activities

Frank went on to describe the scientific purpose of their activity and how it emerged from prior research:

> Frank: Well basically we built a theoretical model of what was already done by researchers in the North Pole... nobody has ever actually traced the path or given a concrete, a concrete statement saying that "oh this is definitely possible"... We just made a model of what potentially was what made it to the South Pole.

Frank situates his research in terms of prior research and what is unknown. They used representational tools (ray tracing in a waveguide) to develop a computational model which would answer a question, whether radiation in the northern ionosphere could scatter to the South Pole. Frank's description not only states that their research is purposeful because it answers an unknown question, but also presents a coherent account of how each of these steps connect in order to achieve a scientific purpose. This is aligned with Ford's description of scientific practices.

4.7.3 Linking joint work to engagement in disciplinary activities

We argue that the structure of Frank's research experience supported him in seeing activities as purposeful and connected, thus we see them as scientific practices. The "step-by-step" nature, daily objective setting, and regular opportunities to work together on joint activities supported the connectedness of Frank's research experiences. Frank's mentor had intentionally taken a "step-by-step" approach, setting a broad project workflow that involved theory and coding. In describing this approach, Frank's mentor emphasized the importance of how each of these steps built off of one another. The mentor's intentionality in planning out several connected steps likely led each of the activities to meaningfully build off of one another. Frank's research team also did a significant amount of co-coordinated working on joint research activities. Within these activities, his mentor was responsible for identifying each step in the process, laying down groundwork, and giving feedback. Their regular activities included having the mentor evaluate students' work as well as Frank evaluating his work with his partner. Frank describes this evaluation as checking how well their code aligns with what they know and what makes sense. We interpret this to mean that they compared their computational models to their conceptual understanding, directly connecting theory and computation together through evaluation. Frank's mentor also discussed how these interconnected activities are intended to support them in asking and answering a research question, which likely supported Frank in seeing the purposefulness of his activity.

4.8 Neil

Neil described the scope of his project as narrow; he developed a device to understand if temperature fluctuations in his lab were impacting the lab's major experiment. In doing this project, Neil, his partner, and his mentor worked fairly close together, with the mentor often being in a nearby room. We argue that these working patterns, along with his mentor's intentional setting of the project structure contributed to a smooth workflow that resulted in Neil seeing scientific activities as connected. We also argue that the narrow scope of the project contributed to his limited sense of purposefulness.

4.8.1 Descriptive accounts of joint work

Though Neil worked in a lab studying Bose-Einstein Condensates (BECs), the project was mainly motivated by a unique challenge faced by the lab; Neil and his partner designed a device to determine if temperature fluctuations in the lab were impacting the lab's major experiment. Neil's mentor had the students design a circuit to measure temperature, create a printed circuit board (PCB) of their designed circuit, use the circuits to collect temperature data, and analyze whether fluctuations in temperature matched fluctuations in the lab's experimental data.

4.8.1.1 Project form and structure

Neil's mentor described the research project structure as "make some widget, use widget." In his description, he emphasized the value of the widget design and measurement connecting to one another:

> Neil's mentor: The whole encompassing thing of course is to take things that have been designed and worked out or whatever and actually make a measurement, or something, or do something, get a good result using what they have done... [The] structure, of all the projects is make some widget, use widget to measure something we didn't know and, I feel like both are equally important experiences to have, in combination... That whole combined package of that is really what I want out of these projects for them...and have the experience to see through the arc of a smaller project.

In this quote, he emphasizes the connectedness of designing a "widget," building it, and using it to conduct an investigation. He uses the phrases "whole combined package" and "arc of a smaller project," which suggests that he sees the project as a contained unit relative to the broader research lab. The idea that the project is a smaller unit comes out on Neil's description; he calls the project "a specific little task."

> Neil: ...We had a specific little task we had to do. Um, and it didn't actually require us to understand fully the uh, physics behind what the lab was working with. We just had to understand our little tiny part, and so uh, we just applied what we know about electronics and circuits to that part and we made our sensor. And so that's sort of how it is overall. You don't have to understand everything about it, you just have

> to understand a small enough portion to um, complete whatever the lab needs done...

Neil states that the bounded nature of the project meant that he didn't have to understand the broader physics behind the lab's main experiment. He states "we just had to understand our tiny part." At the end of the quote, Neil connects the narrow scope of their project to the nature of science, that novices "just have to understand a small enough portion" to "complete whatever the lab needs done."

4.8.1.2 Patterns of interaction

In addition to thinking through the broad scope of the project, Neil's mentor emphasized the importance of anticipating next steps and being available to answer questions. He stated, "There's gotta be a trail. You gotta plot this out, or whatever, beforehand, and know what's coming up, to be able to help them out," valuing knowing what is ahead, and anticipating roadblocks that students would encounter.

When Neil's mentor stated that his role was to plot out a trail, he did not see this as prescribing everything that they were supposed to do. He later described a balance between between giving students some freedom but not being totally lost.

> Neil's Mentor: it's always hard to, like, balance because you want to give the freedom to explore and learn on own... to have some, difficulties, and overcome them and learn... I give them a little bit of room to figure out what's going wrong first...if they sincerely have tried, then that's when I want them to come to me and we can talk about it.

At the end of this quote, Neil's mentor states that he wants students to come to him with questions if they can't figure something out. In Neil's interview, there was evidence that Neil also saw his mentor as available to answer questions.

> Interviewer: What was your relationship with your research mentor like?
> Neil: It was good, I mean, any question we had, he was very helpful. I mean, he showed us, taught us, about all the different circuit things we need to know that we probably didn't know to begin with, like operational amplifiers and that sort of thing. And yeah any questions we had he was there, uh, so yeah I would say it was good.

Neil states at the beginning and end of this quote that his mentor was available to answer questions. He also notes that one of the things that made his mentor helpful was that he "taught us about all the different circuit things... that we probably didn't know to begin with." This aligns with his mentor's statement about anticipating the kinds of things that Neil and his partner would need to know.

One important feature of their team's workflow was that Neil also was in close proximity to his mentor and partner, which offered more spontaneous moments of joint attention. The three of them met twice per week. His mentor was often nearby, even when they were working on separate projects. Neil described their workflow:

> Neil: At the beginning he went over and told us all the uh, all the circuit theory we didn't know and uh we'd go off, we'd leave him in his office, and we'd go off into the electronics room and start playing with components, and trying to get them to work and uh, seeing how, you know, putting the theory to actual application. And we'd do that for awhile, and [our mentor] would come in and check on us, and uh, if we had any questions we'd ask him then. And if we, during all this, if we had any– if nothing worked like, "oh my god," we could just go and grab him, like, "something's wrong!" He'd help us, then later...we ended up making a printed circuit board so we had to, uh, take our little breadboard and design on a computer into a PCB, and uh, when it got to that, he showed us how to use the [software for printing PCBs] program for doing that, and then, he just left us to do it while he went about and did his lab work and stuff and again he'd just come in every once in awhile and just ask questions, that sort of thing.

Neil describes how his partner and he would separate from their mentor to work on their own, but that their mentor would regularly come to check on them and "just ask questions," maintaining involvement in what they were doing. If they ran into roadblocks, they could go to him wherever he was working and get help. Throughout this quote, there is a sense of close spatial proximity between Neil and his mentor, that allows them to fluidly move in and out of shared task alignment and joint attention. There is also the sense that Neil's mentor was seen as available to be interrupted when doing his own work, so that he could respond to students' concerns as they came up.

4.8.2 Engagement in disciplinary activities

4.8.2.1 Engagement in connected activities

In the above quote from Neil, he describes several scientific activities in connected ways. He states that they started by learning circuit theory. Afterward, they engaged in circuit building in the electronics room, which he describes as "putting the theory to actual application." This suggests that he saw the circuit building as directly connected to the theory they had learned before. After they had come up with circuit designs, "we had to uh take our little breadboard and design on a computer into a PCB..." The practice of designing a PCB on the computer directly connected to the breadboard circuit they had built before.

At another point in the interview, Neil gave an overview of their project.

> Neil: We were working in a lab that dealt with uh Bose-Einstein Condensates, and uh, they would calculate magnetic field of these condensates. And it would be based off of some complicated formula but that relied on the amount of current that one of their sensors output. And uh, what they had saw was that there was fluctuations in the current and they weren't sure why. They thought it might have been temperature

> and so uh, me and my partner we, uh, designed a circuit to uh, measure temperature and then we get the data for it to see if there's a correlation between the temperature and the uh, the changes in the current. And it turned out there– there seemed to be and even by manipulating it a little bit by uh, putting like uh, well like a hot air gun against thermostat to cause a temperature to be colder [the thermostat detected the hot air, which led the room to cool itself] and stuff like that, you could actually see spikes...

Neil first described prior work that the lab had done that motivated this project. The circuit design directly stemmed from the research group's hunch that temperature fluctuations might be causing current fluctuations. This suggests that he saw his circuit design as connected to prior work. He then articulates several activities—designing a circuit, collecting data using the circuit, and analyzing the data—in a steady stream of talk using conjunctions "and" and "then." The continuity in his speech also suggests that these activities were connected to him.

4.8.2.2 Engagement in purposeful activities

While Neil engaged in connected scientific activities, we argue that his engagement in scientific activities was less purposeful. In Neil's interview, he was able to describe why the activities he engaged in were relevant to the lab's experiment, but not how the experiment itself fit into a broader scientific research purpose.

> Interviewer: Alright, how much did you feel like you understood how your research fit into the broader goals of the lab?
> Neil: Um, well, I'd say not very well. I mean I understood that they're trying to clean up some data and remove some weird fluctuations but why they're measuring the uh the electric fields of the Bose-Einstein Condensates, that sort of stuff I didn't really understand.

Neil experiences the activities as being purposeful, but his participation is peripheral; he describes that the widget helps the lab "clean up some data." He is also able to articulate the prior observations and data fluctuations in the lab that motivated the project, as shown in the previous section. On the other hand, the broad importance of that data is opaque to him, and he notes that. While he is able to participate peripherally in some activities of the lab by understanding how his project helps the experiment, it has not become a full practice in that he does not understand the broader purpose of the experiment.

The example of Neil suggests that there are at least two aspects of the "purposefulness" of scientific activities. One is seeing how one's activity can contribute to a particular experiment or research group. The other involves understanding the scientific "point" of the experiment and why (in this case) removing current fluctuations would help. Peripheral participation in purposeful activities, as illustrated by Neil, can involve believing that BECs are scientifically important and that his work is contributing to understanding them better.

4.8.3 Linking joint work to engagement in disciplinary activities

The form of Neil's legitimate peripheral participation was characterized by his mentor giving Neil a small contained project that they worked closely on. We argue that this contained structure impacted Neil's limited sense of purposefulness. Patterns of interaction and project form and structure supported Neil's sense of connectedness. Because he described activities as connected, and only somewhat purposeful, we argue that Neil's experience was somewhat aligned with Ford's description of practices.

Neil's mentor structured their activities by plotting out a trajectory and anticipating challenges. Neil described their workflow as involving regular informal checking in from his mentor, and his mentor being available and nearby while Neil was working. We argue that working in close proximity as well as his mentor's responsiveness contributed to a smooth workflow between them where roadblocks could be addressed quickly and Neil's mentor maintained engagement in what Neil was doing. We argue that this smooth workflow likely led to increased opportunities to see the connectedness of their activity.

The structure of Neil's research project, building and testing a device, was mainly motivated by a challenge faced in Neil's specific lab, instead of a broader research question in the scientific community. An understanding of the broader scientific purpose of the lab's activities were not necessary to completing this specific task either. We argue that this contributed to Neil only engaging in the local purpose, without engaging in the broader purpose.

Neil's experience demonstrates that legitimate peripheral participation within a research lab can involve understanding narrow aspects of the scientific purpose—how it contributes to a given experiment—but not fully understanding the broader scientific purpose. This bounded purposefulness can emerge from having students work on a small project where having a broader understanding of the lab's research is not necessary. This contrasts with Frank's experience, where Frank was able to articulate how his research contributed to some broader scientific understanding.

4.9 Cassandra

Cassandra worked with a research scientist on a project creating visualizations of simulations of the early universe. Cassandra described interacting sparsely with her mentor, with most of their work done asynchronously. We argue that this contributed to Cassandra's limited understanding of the purposefulness and connectedness of the visualizations.

4.9.1 Descriptive accounts of joint work

4.9.1.1 Project form and structure

Cassandra describes her project as creating visualizations of simulated data. The flow of their activities was to learn to use the visualization tools, then to create visualizations of their mentor's data.

> Cassandra: ...We were just taking, um, data from our mentor which was, um, theoretical data that he had... He uses this code to generate this data which like, simulates the early, early universe... We visualized his data basically and then just– we weren't able to draw conclusions from it... we did find a possible bug. And I think that, taking it further we would have examined like um, more visualizations to look and see if the bug is real or if this is something else, and then looking at the code directly and trying to figure out like how to fix it or what was wrong.

From Cassandra's description, we see that she was working with data from a simulation that her mentor had created. Her role was to visualize the data through learning and using a visualization package in Python. Cassandra later stated that her mentor did not know how to use this package, so Cassandra and her partner were primarily learning from online resources.

Since we don't have mentor data from Cassandra, we do not know if there were implicit driving questions or learning goals. If there were, Cassandra does not seem aware of them. Moreover, Cassandra does not describe a clearly laid out epistemic approach, or sense of how this project would produce some kind of disciplinary knowledge.

4.9.1.2 Patterns of interaction

Cassandra did most of her research at home on her computer or with her partner, with occasional meetings with her mentor. In Cassandra's post-interview, she described feeling like she wasn't getting the amount of time that she wanted, stating "You know like I did have to push a little to get to work with him..." She goes on to describe their relationship as "scarce."

> Interviewer: So how was- what was your relationship like, with your mentor?
> Cassandra: Umm, scarce...he was a busy person and preferred email exchanges. But I kinda forced him to see me anyways. Cause I don't know I just felt email exchanges were impersonal, and I didn't– if I had questions, you know on the fly, you can't really do that through email. But we– we didn't see him often, like maybe every other week. But we didn't really need him either, so I think like he was easy to get information from, like he wasn't a jerk or anything, but he was kind of an introvert. So you know, I had to work around that.

Cassandra positions the mentor as preferring email or online communication instead of meeting in person. She attributes him preferring online communications to being an introvert and being busy, which she had to accommodate. This gives Cassandra little opportunity for shared task alignment and joint attention. Though Cassandra's mentor does not seem to seek out meetings with her, she does describe how she took an active role in initiating their limited in-person interactions. As she states, “I kinda forced him to see me anyways.” She sees this in-person interaction as being more “personal” and a way for her to ask questions “on the fly.” Later in the interview, Cassandra states that she would have liked to have met with her mentor even more “I think forcing him to see me more, that probably would have been helpful, and probably like picking his brain more.” Cassandra describes her partner as having a similarly distant relationship to her mentor.

4.9.1.3 Accumulating questions that he may not be expecting

Now we discuss one pattern of interaction that came out in the mid-semester interview. Cassandra had many questions related to the nature of their research project, specifically about why they were creating visualizations of simulations, how the simulations were created, and what they expected to learn. She saw her mentor as the source of answers to these questions. Cassandra then described how the process by which her questions were answered involved accumulating many questions over time and asking them all at once.

> Cassandra: But um, but yeah, I saw him last week on like Friday and just kinda talked his ear off for a second. But, (laughs) but um, we’ll be meeting with him on Wednesday... [Cassandra lists several questions about the details of their project]... I guess what I would want to know the most is, well, how did we first like make a simulation for how the matter was distributed. You know? That to me is really interesting. And the program that we’re, the initial conditions were put into, or like, what? How did they write such a program? I don’t know, that’s really exciting. And why did they choose this one as opposed to– Cause there’s a bunch of them out there. Um, and how does it compare to what we know? You know what I mean?...Or the whole thing about dark matter like um, like we know, we don’t really know what dark matter is. Do we? So how did they apply that to their model? Like how did they apply that to their simulation? How did they get a number? How did they quantize the distribution of dark matter in the universe? Like we know, so it’s all really interesting, those are all questions we’ll be asking him on Wednesday. I hope he’s ready.

Cassandra describes how the previous Friday, she had “talked his ear off” with her questions, and then names a long list of other questions she is currently grappling with, that she intends to ask her mentor about on Wednesday. Her wording of the phrases “talked his ear off” and “I hope he’s ready” positions herself as taking an active role in seeking out answers to her questions, and perhaps that her mentor does not expect her to be asking them. This kind of relationship has a very different feel from the relationship between Neil and his mentor, who intentionally anticipated students’ questions, proactively checked-in with them, and made himself available to answer them.

4.9.2 Engagement in disciplinary activities

4.9.2.1 Limited purposefulness and connectedness

In the mid-semester interview, there is evidence that Cassandra isn't getting to see the connections between her work and other scientific activities, namely how it connects to prior work generating the simulated data.

> Interviewer: How do you feel like it's going?
> Cassandra: Um. So far so good, although we're still not- one thing we're not really clear about, and that's uh, we're taking theoretical [simulated] data and we're basically making it very visual. But we don't– it hasn't been made clear to us, the simulation that the data's been run through... we don't really have an understanding yet of what, like the initial conditions were for the data that we got and then um, I guess there's different simulations you can run these conditions through, and so why he chose this one as opposed to others. So we're gonna talk to him about that on Wednesday.

Cassandra points out not knowing what the initial conditions are for the data, or how it connected to prior scientific activity of generating the data. In particular, she doesn't want to just know what the initial conditions were, but also how those were chosen. We argue that she wanted to connect the simulated data connected to some theoretical understanding that led to the initial conditions.

Cassandra also had questions about the broader purpose of their research activities. When asked about what would count as "success" to her in the project, she said it would be having an understanding of the importance of their work:

> Cassandra: Why are we putting it into pretty pictures? Like how is that gonna help us?... Understanding the bridge between numbers and something you can look at. I mean, that would be a success. Seeing the fruits of your labor, I don't know. Cause why do we do that? Why are we creating this model of something we'll never see? What, how is that going to add to the scientific community? You know?...It would be interesting to see if we learn something from seeing this data.

At the start of this excerpt, we again see limited connectedness; Cassandra explicitly asks what the "bridge" is between the simulated data and her visualization work. Cassandra also describes a desire to understand the scientific purpose of this work. She specifically asks "how is that going to add to the scientific community?" This illustrates that she understands that research should be relevant to the scientific community, and she has some sense that her work is; however, she does not understand the details of what her work could contribute to the community. At the end of the statement, she is curious about whether or not they will "learn something from seeing this data." Here, Cassandra is not only asking what's the purpose of the endeavor, but also how their work might connect to some kind of scientific insight.

4.9.2.2 Linking joint work to engagement in disciplinary activities

We argue that in Cassandra's case, her limited sense of purposefulness and connectedness of scientific activities stemmed in part from features of joint work between Cassandra and her mentor. Cassandra's interactions with her mentor were primarily limited to email exchanges and occasional in-person meetings that she had to seek out herself. Unlike Neil and Frank, Cassandra had limited opportunities to co-work with her mentor. Cassandra explicitly connects being limited to email exchanges to not having questions answered: "I just felt email exchanges were impersonal, and I didn't– if I had questions, you know on the fly, you can't really do that through email." This setup led to her accumulating questions over time and then asking them to her mentor all at once. We argue that having fewer opportunities to ask these questions, rather than having immediate feedback while working alongside mentors, led to Cassandra having a limited understanding of what she was doing—a low sense of connectedness and purposefulness.

One might wonder why Cassandra did not eventually gain an understanding of connectedness and purposefulness given that she was so proactive about saving up questions and asking them. The activity of asking questions in meetings occurred as a separate activity from her day-to-day work on the visualizations. We believe that the discursive separateness of her engagement in day-to-day activities and discussing a broader purpose and theory likely contributed to her sense of a lack of connection between her day-to-day activities and the insights about the purpose of her work (and its connections to previous work) she may have gained during question-and-answer sessions.

The asynchronous workflow was also another contributing factor to Cassandra's mentor being unresponsive to Cassandra's questions. Cassandra's role on the project required her to develop expertise using a visualization package that her mentor did not know how to use, so she and her partner learned from online resources rather than their mentor, and had fewer opportunities to coordinate activities. Allowing mentees to develop complementary expertise to the mentor doesn't necessarily lead to separation of day-to-day activities; the mentor would need to more deliberately structure activities to have opportunities for immediate feedback—for instance, by using Neil's mentor's strategy of working one room over and regularly checking in.

Cassandra's case reveals another form of LPP within physics research. As the mentee, Cassandra played a more active role in facilitating interactions between students and mentors than Neil and Frank needed to do. However, having fewer opportunities to engage in the kinds of shared task alignment or joint attention with a mentor that characterized Frank's and Neil's experiences still led her to see the physics research activities as not fully connected nor purposeful. Based on this analysis, we find that Cassandras research experience resulted in limited opportunities to engage in scientific practices.

	Connectedness	Purposefulness	Joint work
Frank	Articulated connections between theoretical and computational aspects of project	Articulated that purpose of the research project was to confirm/disconfirm a hypothesized mechanism for an empirical observation	Project was laid out "step by step" by mentor. Oscillated between working independently and co-coordinated activities.
Neil	Articulated connections between the circuit theory, circuit design, and data collection	Articulated how activities helped the lab's experiment, but not the purpose of the lab's experiment	Project described as "build widget," "test widget." When working independently, mentor would check in on them and be available to answer questions.
Cassandra	Limited connectedness between theory and the starting assumptions designed into the simulation	Limited sense of how the work would help the scientific community.	Worked asynchronously, with infrequent mentor communications. Accumulated questions over time.

Table 4.2: Summary of Connectedness, Purposefulness, and Joint work across the three case studies.

4.10 Discussion

In this paper, we illustrated various forms of legitimate peripheral participation in the physics research community as it played out in undergraduate physics research experiences. Using student interviews, we analyzed the extent to which students engaged authentically in scientific practices, defining scientific practices holistically as being activities which are purposeful and connected. Drawing from situated learning theory, in which engagement in activities depends on the setting, relationships, and joint activities, we outlined aspects of the research projects' structure and patterns of interaction with mentors that contributed to the extent to which—and the ways in which—students saw activities as purposeful and connected.

Although much work has focused on students' engagement in particular science activities such as argumentation [118, 177], developing mechanistic accounts of phenomena [119], and scientific reasoning [48], little work has focused on how students understand the purpose of those activities or their connection to other activities. We attend to activities at a meta-level, focusing on how these activities fit together in service of a broader purpose. By applying Ford's framework to cases of undergraduate research experiences, we hope to give research mentors more tools to be responsive to students seeking connectedness and purposefulness in their work.

We cannot use these three case studies to build generalizations within this population of students or across populations of students [84]. However, we can use this work to build theoretical generalizations about how project form and structure, and patterns of interaction impact connectedness and purposefulness (as illustrated in Figure 1). In the next few sections, we begin this work.

4.10.1 Our analytical approach helps us build claims about how joint work can support engagement in scientific practices.

Prior research on undergraduate research has insightfully identified the kinds of research activities that students engage in when doing UREs. Our research complements this prior work by showing some of the finer-grained details of what that engagement looks like.

While surveys can capture the extent to which students engaged in specific scientific activities, interview-based and other qualitative research allows us to characterize the extent to which and ways in which those scientific activities were connected and purposeful. Consider this item from the Undergraduate Research Questionnaire:

> Data analysis is something I can do.

Many students might agree with this item, but the item does not capture the extent to which their participation in the activity of data analysis is connected to other activities, or whether the student understood the scientific purpose. We see those features of scientific activities as being essential to authentic participation. To make this example more concrete, Cassandra and Neil would likely agree with this statement. But the details of their participation differ. Neil's engagement in data analysis directly stemmed from measurements he had taken using the circuit he had built, and he saw his work as helping the research group decide whether some unexpected results of previous experiments were caused by temperature fluctuations in the room. In contrast, Cassandra analyzed visualizations of the simulated data, but she still had many questions about where the data came from and why her work was important. We see these details of knowing why a particular form of data analysis makes sense for a given set of data and having an understanding of how the data was produced from an instrument (or simulation) as important aspects of doing authentic science that would likely impact students' long-term engagement.

We do think it would be possible to design survey items that assess the degree to which students view scientific activities as purposeful or connected, but interviews leave room for exploring the nature of that purposefulness and connectedness. Consider the survey item "I understand the broader purpose of the experiments I am conducting" [178]. Frank would likely agree with that item, but his survey response wouldn't allow us to examine how his participation in activities "hangs together" and the sensibility and coherence of the logic behind those connections, from both Frank's and a researcher's perspective. In a different vein, Neil might agree or disagree with that item, depending on whether he was thinking about the purpose of his project within the lab, or the purpose of the lab's experiments in the broader scientific community.

Analysis of interviews allows us to characterize these different forms of LPP and how they might impact students' future trajectories into the scientific community. Going back to the example of Neil and Cassandra's different experiences with data analysis, Neil has engaged in data analysis as connected to instrument development and a driving question. Even though he does not have full understanding of the broad purpose of the lab's experiment, having these opportunities for understanding connectedness and purposefulness of practices would likely support deeper participation. In contrast, Cassandra's experience with data analysis was disconnected from the generation of simulated data and the purposes of simulating that data (i.e., less access to scientific practices). Cassandra's participation in the physics research community of practice is more limited, and there are fewer clear avenues for deeper participation in the future.

An area for future study would be to collect and analyze *in situ* data of students and mentors to see how connectedness and purposefulness are supported within interactions. Our interviews suggest where one might focus attention in such analyses, such as how students' questions are addressed and the spatial orientation of students and mentors.

4.10.2 Prevalence of lack of broader purpose

Across our broader set of data, many students did not describe having regular opportunities to contextualize their activities within the broader scientific purpose. Neil stated that he was unfamiliar with the broader purpose of the research lab's activities. He later stated that this stemmed from not having taken advanced coursework. Bounded senses of purpose of research activities likely stemmed from multiple factors such as limited amount of time and level of background knowledge. We believe that this infrequent examination of the "10,000 ft view" of research is also fairly common in science; while focused on wiring a detector, debugging code, or "cleaning" data, a researcher might find little time to reflect on the broader purpose of their work—though of course they are capable of doing so.

We also note that a lack of sense of broader purpose is not necessarily a bad thing. Mentors are managing multiple goals and constraints, such as limited time, wanting students to have an enjoyable experience, and wanting to make research progress [81]. Scaffolding students' understanding of the broader purpose might not rise to the top of students' and mentors' goals. Neil's mentor, and likely other members of their subdiscipline, would probably not mind that Neil did not understand the broader purpose. In a later part of the interview, Neil suggested that because he did not have to understand a lot of background knowledge, he felt capable of doing research. In contrast, Cassandra's lack of understanding of the broader purpose of her activity made her consider switching into another area of physics research. So, while students' engagement in connectedness and purposefulness interact with their satisfaction in ways that likely impact students' long-term trajectories, Cassandra and Neil illustrate how those interactions vary from student to student.

4.10.3 The racialized and gendered nature of connectedness, purposefulness, and joint work

This work is part of a larger study in which we are trying to understand shifts in students' identity and participation for the purpose of knowing how to better create physics pathways for students who have been historically marginalized. In this section, we consider aspects of students' racialized or gendered identities as they interact with joint work and students' satisfaction with connectedness and purposefulness of their research. How interactions become gendered and racialized is an important area of study. While our analyses have not included race and gender explicitly, we do believe they are at play in our data, and we think our analyses motivate future work on race and gender in studies of UREs.

If it were commonplace that connectedness and purposefulness were missing from UREs we would expect students to react differently. Neil and Cassandra illustrate variations in the degree to which students care (or not) about purposefulness at multiple grain sizes. Neil seemed satisfied with understanding the local purpose of his research within the research group, and not understanding the broader purpose of the lab. Within Cassandra's interview, she was emphatic about wanting to understand how her work was connected to prior work, and what purpose it could serve within the scientific community. It's plausible that this would unfairly marginalize students who value their working having relevance within a scientific community. Other research suggests this may be the case for women and students of color [5, 145]. For example, Tobias describes the lack of a "narrative thread" and context as being one reason why students' leave physics [145]. Depending on how well students' desires to understand connectedness and purposefulness fit with what is afforded by the projects, they might have positive or negative experiences in UREs that could impact their long-term trajectories.

We also believe that mentoring behaviors such as leaving the burden on students to schedule regular meetings and ask questions would disproportionately favor more aggressive students (aligned with stereotypically male socialization [5]) and students who have greater comfort talking to faculty (e.g., students from college-educated families, and students of higher socioeconomic status [37].) We encourage research mentors to reflect on how their forms of communication might privilege students who are white, male, and high socioeconomic status, and consider how they might lower the barrier to interactions. For example, creating dedicated time and space to co-work with a mentee, as we saw in Frank's case, would support mentors in being more responsive to mentee's questions and ideas.

There are many ways that gender and racial dynamics play out in the lab, but in this section, we chose to foreground aspects that pertain to connectedness, purposefulness, and joint work. In future work, we plan to discuss students' long-term identity trajectories and consider how their histories and identities are interacting with the way they experience physics research.

4.10.4 Practical Implications for UREs

This work demonstrates how the design of research experiences and interactions between mentors and mentees can impact what students learn in research experiences. This points to features to attend to when supporting undergraduate researchers. We argue that URE mentors should attend to the ways in which scientific activities are meaningful with respect to one another and to a broader scientific purpose, and the logic behind how activities are coordinated. For example, mentors can design research experiences with an overarching flow in mind, and support students in understanding why this flow in sensible. We acknowledge that seeing activities as connected and purposeful takes time, so it is important to think ahead about how activities might come to be connected to one another and to a scientific purpose in coherent ways. Such deliberation may increase students opportunities to engage in scientific practices.

Designers of environments such as 299B should also consider giving students opportunities to reflect on connectedness and purposefulness. Within this environment, course instructors could support students in drawing out connections between individual activities and a scientific purpose.

Finally, we also note how the environment and workflow between mentors and mentees enables more responsive relationships which ultimately support connectedness and purposefulness. We argue that it is not enough to just address students' concerns as they come up. Mentors should also consider how their setting and workflow might lower the barrier to starting and maintaining conversations. For example, mentors could deliberately sit in the same room as mentees over some periods of time so mentees can ask questions as they come up. In working together, mentors could invite reflection on the broader purpose of their work or discussion about how one practice feeds into another. Students' construction of these answers likely requires dialogue with people who have disciplinary expertise in that project area. Arranging work patterns to be more collaborative would support that. Work by Museus suggests that mentors proactively making support available and fostering more collective working environments can be especially beneficial to students of color [179]. Our analyses illustrate how challenging it is for students to gain an understanding of connectedness and purposefulness of scientific activities on their own, and so mentors should explicitly support this big-picture framing of their project.

4.10.5 Future studies of identity development

Future work will longitudinally study how participation in UREs impacts students' identity trajectories with respect to the physics research community of practice.

While we have conceptualized participation in authentic science practices within a physics community of practice as centered around the connectedness and purposefulness of those practices, we value other learning outcomes as well. Future work should consider a broader definition of authentic participation, including students' conceptualizations of the physics community, affective dimensions such as their sense of satisfaction, and how they are positioned by mentors and peers as belonging (or not) within the discipline. Our other data hints at nuanced connections among these aspects of students' participation. Neil's engagement in bounded purposefulness, without needing to understand the broader physics behind his experiment, connected to his sense that he was able to do research. In a different vein, Cassandra's lack of broader purpose of her work, along with her desire to understand that broader purpose, eventually led her to pursue a different subfield of physics. Future work will describe the nuanced ways that students' initial participation in the physics research community bears on their long-term participation.

We also find it worthwhile to broaden our view of what it means to participate in the physics research community. This is motivated in part by Wenger's study of claims processors, in which he describes regular office birthday celebrations as important to the local community of practice. In our own interviews, we similarly found that physics communities participated in activities that one might not think of as central to the physics discipline, but that still mattered for students' identity development. For example, bonding over video games or other aspects of "geeky" culture are not particularly important to enacting physics research practices, but not participating in such activities can negatively impact students' access to physics. Other students described attending regular social outings with their research groups, or talking with research mentors about mutual hobbies. We see these activities as part of what membership in the physics community means, but they have not been as foregrounded in conceptualizations of the domain.

Finally, future work will also explore how students' participation in physics is mediated by race, gender, age, and other dimensions of student identities. Several interviews suggest that students are noticing and contending with normative physics identities of who is typically a physics major. It would be worthwhile to analyze the ways students navigate normative physics identities and consider how students from diverse backgrounds are differentially impacted. Understanding how the physics research community marginalizes students would be an important step toward fostering more inclusivity in physics.

Chapter 5: Analyzing Identity Trajectories Within the Physics Community

5.1 Abstract

We analyze the identity trajectory of a single case study, Cassandra, within the physics community. We focus our analysis on two settings in the physics community: an undergraduate research experience, and undergraduate coursework. We use video data from three interviews (spanning roughly fifteen months) to longitudinally analyze shifts in participation. We discuss Cassandra's experience through two constructs: *normative identities*, Cassandra's sense of the valued roles within physics, as well as *personal identity*, who Cassandra is within the physics community and the extent to which she aligns with *normative identities.* In attending to shifts in the alignment between personal and normative identities, we identify several *entry points*, or salient events that open up new opportunities for participation.

5.2 Introduction

> *"This is the first semester where I've felt like I belonged in physics. Like I didn't feel like an outsider or like, oh, I'm not as good as everybody else, you now? This semester I started to realize that I'm just as bad and just as good as everybody else...Now that I'm getting to know more people, I'm realizing that everybody's struggling. We are all kinda in this thing together." - Cassandra, interview*

In the quote from Cassandra, an undergraduate student in physics, we see some of the complicated ways that one's sense of belonging and sense of self are intertwined with one's sense of physics competence and relationships to others in the community. Cassandra describes realizing that she's "just as bad and just as good" at physics as her peers, reframing her weaknesses as part of a common struggle, instead of evidence that she doesn't belong. Coming to see peers as having strengths and weaknesses changed the way she saw herself within the discipline and in turn, shaped her affiliation with other physics students. This quote illustrates how Cassandra's *identity*, who she is within the community, is forged within relationships with other members of the community, and how changes in one's relationships can lead to shifts in identity.

This chapter seeks to understand how student identities are shaped in relation to students' evolving participation in the physics community. Understanding identities, and particularly changes in identities, can help us understand the processes by which students move into or out of the physics discipline.

This work is especially important, given that representation and recruitment of women and underrepresented minorities is severely poor in physics [2]. Many women and underrepresented minorities have the potential to be talented scientists but are turned away by harsh practices and the unwelcoming culture of STEM disciplines [5–7]. This misalignment between students' identities and the normative practices of the discipline even turns away students who are successful at coursework [5, 8].

Common ways of discussing retention fail to account for the complexity of students' experiences, and can invoke goals of assimilating students into the current system [4]. Given the diverse backgrounds of students, we believe it is important to move beyond the "pipeline" metaphor of retention, which assumes a singular pathway for students to become scientists [9, 10]. Instead, we ask how one might foster a diversity of successful STEM pathways. An important step toward fostering a diversity of pathways is to closely study individuals' trajectories as they move through learning experiences. This paper expands our understanding of students' trajectories into or out of physics by studying mechanisms that impact the development of identities within interactions. Understanding the nuanced ways that students are supported (or not) in physics can point to how we can create conditions in which a diversity of students can succeed.

In this paper, we focus on a single case study, Cassandra. As a white woman, transfer student, and older than other students, Cassandra holds multiple intersecting nondominant identities in undergraduate physics which contribute to unique external pressures and her experiences of marginalization. We discuss Cassandra's experience through two constructs: her perception of *normative identities*, the accepted and valued roles within physics, as well as *personal identity*, who Cassandra is within the physics community and the extent to which she aligns with *normative identities*. Cassandra experienced both shifts in personal and her perceived normative identities, which contributed to her gaining membership in the physics community. These shifts in her participation over time point to several *entry points* that opened up new opportunities for Cassandra. After articulating the challenges and entry points in Cassandra's trajectory, we discuss implications for making physics more inclusive.

5.3 Theoretical Framework

In this section, we elaborate on how we conceptualize identity and the aspects of identity we choose to foreground in this paper. We first present *situated learning theory*, which describes identity as who one is within a community of practice. We then describe prior work which studies how identity relates to disciplinary practices, and introduce the concept of *normative identity*. Finally, we briefly outline prior work that has discussed how identity development is impacted by students' gender, race, and socioeconomic status.

5.3.1 A situated perspective on identity trajectories

While there exists a breadth of perspectives on identity in education, we draw on Lave and Wenger's *situated learning theory* and Holland's *practice theory of identity* to understand identity development. Within situated learning theory, identity and learning are inseparable from participation within a *community of practice* [41, 59]. Newcomers to a community of practice engage in *legitimate peripheral participation*, interactions between newcomers and old-timers on authentic joint work of the community. These interactions facilitate opportunities for new kinds of participation in the community, which is synonymous with learning and identity formation.

Within this paper, we conceptualize the relevant community of practice to be the physics community. The physics community of practice is distributed across many settings and its members engage in a wide set of physics-related activities. For example, being part of the physics community can mean taking or teaching courses, doing research in a research group, attending colloquia and seminars, and going to a departmental holiday party. Our analysis specifically zooms in on two major settings within the physics community, physics research activities and undergraduate student academics. These two realms are connected but distinct. Physics research involves many of the same people that participate in undergraduate coursework. In both settings, old-timers in the community play similar roles in supporting newcomers in learning the practices of the discipline. There are also nuanced differences between the settings. The common practices, norms, and what counts as being good at physics all look different. Becoming an "expert" in the physics community writ large, in part, involves understanding these differences between the settings.

Lave and Wenger do not provide many tools for understanding identity beyond participation in practices, so we also use Holland's *practice theory of identity.* This perspective on identity includes both how one understands oneself, but also how one is recognized by others. These two aspects interact with one another; how one is seen by others impacts their understandings of themselves, whereas the ways that one sees oneself can impact the identities that others ascribe to them [3, 67, 69]. Holland emphasizes this dual nature of identity, which is "always, but never only 'in' the person, never entirely a matter of autobiography nor, on the other hand, entirely reducible to membership (voluntary or involuntary) in culturally, politically distinctive groups or social categories." We call descriptions of an individual (or the self) in relation to a community *positioning* (e.g., saying "she belongs in physics" positions her as belonging within the physics community).

In this paper, we focus on *identity trajectories*, longitudinal (long-timescale) descriptions of how students' identities shift within a community over time [3, 33, 41, 69]. In Jackson and Seiler's [69] study of undergraduate STEM identity, they identify three forms of trajectories: inbound (greater identification with STEM), outbound (lesser identification with STEM) and no changes in identification with STEM (c.f. [41]). They model identity trajectories as the accumulation of identity-shaping experiences that contribute to one's identity *thickening*, or stabilizing over time.

Disciplinary identity is also inseparable from one's participation within the disciplinary community. Identity can also be thought of as how one participates in practices of the community, which Urrieta refers to as *procedural identity* [72]. In Carlone and Johnson's identity framework, doing scientific practices, as well as one's competency in science are all parts of one's scientific identity [31]

Within the physics community, we conceptualize physics identity to include internalized ideas about who an individual is with respect to physics, ideas that others have about the individual, and how one participates in the physics community and practices of the physics community. We seek to understand *identity trajectories*, changes in one's identity within the physics community over time. Other work has shown that these trajectories are shaped by the context and activities in which students engage, which we elaborate on in the next section.

5.3.2 Identities connect to disciplinary practices and context

Prior literature has studied how disciplinary identity is dependent on the locally enacted disciplinary practices. Within a given classroom, the prominent activities and practices impact how students understand the discipline, and the extent to which they identify with that discipline. Different settings also afford different resources for identity development. Nasir and Cooks describe several resources for identity development within a setting, including the kinds of artifacts in the setting, interpersonal connections, and ideas one has about oneself and what is valued within the setting [180].

For example, work by Boaler and Greeno has shown that engaging in rote plug-and-chug in high school math classrooms led students to develop negative mathematics identities [6]. Carlone [71, 172] discusses how disciplinary competence is constructed in science and engineering classrooms. Her work articulates what is recognized as doing science within a classroom community, and how that impacts who is recognized as good at science in those settings. For example, within a reformed science classroom, doing science well might entail developing coherent explanations of phenomena, and drawing connections between concepts. Students are recognized by others (and themselves) as "scientific" when they can perform science in these ways. These studies illustrate how disciplinary identities are shaped by the kinds of disciplinary activities that occur in that context, the resources available for identity development, and the kinds of available subject positions in those settings. In order to describe the extent to which students' identities relate to the locally celebrated subject positions, we draw on the notion of *normative identities*.

5.3.2.1 Motivating expansive look at physics communities

While most of the prior research outlined above has focused on narrow contexts, such as a classroom, we expand our analysis to consider students' engagement in many kinds of physics contexts for this study. We take this expansive approach because undergraduate physics majors experience being a part of the physics community in several informal and formal contexts, including courses, study areas, and research labs.

We align our work with other research that has shown that this variety of spaces can support identity development at the undergraduate level. A study by Goertzen, Brewe, and Kramer describes how a student lounge and study area, social and academic activities run by an active student group, and a peer-educator program all impacted undergraduate students' long-term engagement in physics [165]. Other research has shown that informal peer study groups impact students' learning and persistence in a discipline [18, 181]. Undergraduate teaching opportunities such as Learning Assistant (LA) programs can be sites of identity formation [163, 165]. Student-led retention programs, offering services such as bridge programs and mentorship, can be important sites for fostering community among undergraduate students, and likely support identity development [11, 168].

With the exception of Goertzen, Brewe, and Kramer [165], we know of no other studies which have taken into account a diversity of these kinds of contexts in a single case study. By doing so, our analyses make an original contribution to the literature by identifying how multiple contexts afford different opportunities for identity development.

5.3.2.2 Normative and Personal Identities

In this section, we describe how we analyze identity development through students' perceptions of *normative identities* and *personal identities*. While *normative identities* was first introduced by Cobb et al., we also draw from work by Carlone, Scott, and Lowder [71], Tonso [33], and Foor, Walden and Trytten [37] to inform our definition of *normative identities* in this paper.

In their study of high school mathematics learning, Cobb et al. [42] describe *normative identities* as who is recognized as good or competent at mathematics within a given classroom, and is typically associated with what it means to know or do mathematics within that setting. These normative identities are not tied to any given member of the classroom, but rather are idealized types of members of the community. For example, in a reformed physics class, the normative physics identity would be someone who explains their reasoning and looks for real world examples of physics concepts. Normative identities are aligned with Stevens, O'Connor, and Garrison's notion of *accountable disciplinary knowledge*, or what counts as doing engineering competently [3].

We extend Cobb et al.'s notion of normative identities to include what is accepted in physics (instead of merely what is good). That is, we use the term *normative* to refer to acceptable or recognizable ways of being in physics. This includes aspects of identities that are not associated with disciplinary practices or doing well in the discipline. For example, within physics it can be normative to enjoy science fiction and play video games (c.f. [182]). These identities are normative in the sense that they are recognizable and accepted hobbies in physics, though they do not centrally contribute to knowledge-building about physical phenomena. We include aspects of *normative identities* that are recognizable but not explicitly valued because this bears on students' senses of belonging within the discipline.

In broadening Cobb et al.'s definition of *normative identities*, we draw from work by Carlone, Scott and Lowder [71] which identifies *celebrated subject positions* in a classroom. These subject positions can pertain to specific epistemic practices and connect to what it means to do science well in a classroom (e.g., explaining one's reasoning). They can also be connected to ways of interacting with peers that is not necessarily associated with what it means to do well in a classroom. Carlone, Scott, and Lowder identified celebrated subject positions such as being a "people pleaser" as well as teasing and name-calling of other students.

Similarly Tonso [33] studies the available subject positions at an engineering school and identifies several social and academic roles that students can occupy. These available subject positions sometimes connected to disciplinary practices and were highly gendered. For example, students who were referred to (by peers) as "super-engineer nerds" were good at integrating real-world knowledge with textbook knowledge and students who were named "sorority women" were outgoing women who took on campus leadership roles. Other students who did not identify with these available roles were not recognized as belonging in engineering (by themselves and by peers). This work highlights how these available subject positions, even those that are not centrally tied to disciplinary practices, bear on students' recognition by others and themselves as an engineer.

In a different vein, Foor, Walden, and Trytten identify normative aspects of engineering culture, and how it is associated with socioeconomic status and background [37]. For example, students are expected to be available for office hours, which disadvantages students who have to work full-time jobs. Engineering culture also benefits students with certain forms of cultural knowledge, such as how to secure internships and access studying resources. While Foor, Walden, and Trytten do not locate these hidden forms of knowledge within "roles" or "identities," they do explicitly associate this knowledge with engineering students from dominant groups.

Cobb et al. describes students' *personal identities* as how one see themselves and one is seen by others within a setting, including how one relates to the normative identities of the classroom [42]. Cobb et al. outline three ways that personal identities relate to normative identities: 1) Personal identities *align with* normative identities; in their study, this was identified by students describing themselves as fitting into a normative identity or aspects of a normative identity. 2) Personal identities can *comply with* normative identities; this was identified by students "merely cooperating with the teacher" and doing math that aligned with the teachers' expectations (e.g., "playing school" [14]), 3) Personal identities can *resist* normative identities; students "develop oppositional identities" to the the classroom expectations and act in oppositional ways. They identified the relationships between *normative* and *personal identities* in interviews with students.

In this paper, our definition of *normative identities* includes the broad set of roles that are available to students as acceptable ways of being in the discipline. These roles include what is recognized as competent in physics (e.g., being able to solve a problem correctly) as well as the accepted social roles that are less centrally tied to doing physics (e.g., having an in-depth knowledge of Star Wars). We define *personal identities* to be how one see themselves, how one is seen by others within a setting, and how one engages in the practices of the discipline. We look for the relationship between personal and normative identities, either as *aligning, complying with,* or *resisting.*

5.3.2.3 Normative identities and perceptions of normative identities

In this paper, we attend to *Cassandra's perceptions of normative identities*, rather than the *normative identities* themselves. In the studies described above, *normative identities* and *celebrated subject positions* are identified through classroom observations [42, 71]. Tonso identified available subject positions through ethnographic observation and analysis of seventeen student interviews. In contrast, our paper focuses on Cassandra's perceptions of *normative identities* in physics, through analysis of interviews with Cassandra. Because we are interested in understanding Cassandra's belonging within the physics, her perception of what is normative likely impacts the extent to which she identifies with physics.

We believe that Cassandra's perceptions of normative identities would correspond (but not 100% overlap) with what other members of the physics community or an outside observer would identify as normative. Normative identities are, in part, constituted by the perceptions of those within the community (including Cassandra). Because different individuals hold different vantage points of the physics community, we would expect differences across what individuals perceive to be normative. Additional analyses, such as classroom observations or analyses across multiple interviews, would be necessary to understand *normative identities.* Cassandra's perceptions of normative identities, are a useful starting point for understanding *normative identities.* Within this paper, we label Cassandra's perceptions of normative identities as *normative identities*, for short, and acknowledge that *normative identities* as perceived by Cassandra is only a slice of the broader construct. [1]

5.3.3 Identity development is mediated by gender, race, and socioeconomic status

Now, we briefly summarize prior research which seeks to understand how gender, race, and socioeconomic status impact identity development.

The sets of identities available to students can be gendered. In Tonso's study of undergraduate engineering students, both men and women were able to be recognized as being successful socially, but only men could be recognized as competent academically [33]. In her study, women who performed engineering as well as the competent men were simply not recognized as being academically achieving.

Other work illustrates how students of color experience racism and stereotyping. A study by Rosa and Mensah [30], which studies the pathways of successful

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[1] In discussions of early analyses, we have found that other researchers have used the phrase *Cassandra's perceptions of normative identities* to cast doubt on Cassandra's accounts and imply that her perceptions do not have overlap with what an outside observer would find. We choose to use the label *normative identities* to refer to Cassandra's perceptions to avoid sending the message that we question Cassandra's interpretations of what is going on.

black female physicists, discusses how persistent racism impacts students' participation within the discipline. Women in their study experienced microaggressions such as dismissiveness from teachers, exclusion from study groups, and having peers withhold resources. Work by Martin [183] discusses the masternarratives about African American students and math, and how his African American math students forged counternarratives that explicitly contested masternarratives. Work by Ong [184] illustrates the kinds of ways that women of color navigate their racialized experiences by implementing strategies such as passing. Foor, Walden, and Trytten [37] describe a case study of an undergraduate student, Inez, who enters engineering school as being a minority along several dimensions, including socioeconomic status, limited experience with higher education, race, and gender. Because she does not have as much social capital and access to the unspoken "rules of the game" as her more affluent peers, Inez remains at the margins of the engineering school. This limits her participation and identity development in engineering. This prior work illustrates how race, gender, and socioeconomic status impact the kinds of identities available to students and the processes by which they develop identities.

5.4 Analytical Approach

5.4.1 Context

The University of Maryland, College Park Campus is the state's flagship public school. Roughly 27,000 undergraduate students are enrolled per year. The physics department typically has about 50-60 first-year freshmen and transfer students per year. In this section, we describe the research and seminar context that was the focus of this study. We also describe other physics spaces that Cassandra and other students were embedded in.

5.4.1.1 Research and seminar context

Physics 299B: The Physics Toolbox, at the University of Maryland, College Park, is a seminar that was co-developed and co-taught in 2013 and 2014 by Quan and another instructor. In each Spring since then, the course has been taught by other instructors. Cassandra took the course in a semester that was not taught by Quan, but Quan met regularly with the course instructor to reflect on the course and discuss lesson plans. Quan was introduced to students as a researcher studying the course. She attended every meeting of the course and regularly participated in discussions.

299B introduces undergraduate freshmen and first-year transfer students to authentic physics research. All first-year physics majors who were not currently engaged in research were encouraged to enroll during advising. The course typically enrolls 15–20 students in a given year. Instructors recruited mentors (faculty, postdocs, and advanced graduate students) whom they felt would create meaningful learning opportunities in their research labs. Mentors proposed projects of reasonable complexity for a first-year undergraduate to complete in one semester. Students were matched with mentors based on topical interest. For 3–5 hours per week over 15 weeks, students worked with their mentors on research projects. Research projects spanned experimental and theoretical areas of physics and astronomy.

In 299B, Cassandra worked with an astronomy professor on a project developing visualizations of early galaxy simulations. After the course ended, she continued working with her research mentor on a different project modeling globular clusters for at least another year after 299B ended.

5.4.1.2 Physics student communities

Students at the University of Maryland Physics Department have opportunities to participate in social and academic communities. The department has an active chapter of the Society of Physics Students (SPS). The club coordinates regular outreach, fundraising, professional development opportunities, and weekly seminars geared toward undergraduate students. In addition, the club also runs a tutoring center Monday through Friday evenings, a program that was initiated in 2013. SPS tutors tend to be junior and senior level students, as student tutors are required to have taken quantum mechanics. SPS is comprised of 50 active members, but also serves approximately 150 undergraduate students through tutoring, socials, outreach and seminars.

While the physics department spans several buildings across campus, undergraduate students most commonly gather in the John S. Toll Building, and occasionally in the Physical Sciences Complex (PSC). Toll is the building where most undergraduate physics lectures and labs are held and there are multiple classroom-style meeting rooms in Toll where physics students study. At the center of Toll, there is an undergraduate student lounge where students study, do homework together, and socialize. The lounge is commonly discussed in our data set as a salient aspect of the physics student community, both as a place where some students felt welcome and a place where other students felt explicitly unwelcome.

The department runs an NSF funded S-STEM program, *Focus on Physics*, which supports 8–10 S-STEM scholars per year. The goals of the program are to increase student retention through providing scholarships to students with financial need, building community among the cohort of scholars, and supporting identity development. A requirement of the program is that students participate in a series of seminars, including Physics 299B. Fewer than half of 299B attendees are S-STEM scholars, but all S-STEM scholars are required to take (or have taken) 299B. Focus on Physics is a founding member program of the Access Network, a national network of programs at eight undergraduate institutions. The Access Network is focused on supporting inclusiveness and diversity in STEM through student leadership, community building, and authentic physics opportunities.

5.4.2 Data Collection and Selection

This work is embedded within a larger study which aims to understand students' shifts in participation within the physics community of practice. In the focal semester, Quan collected classroom videotapes, observations of students in their labs, pre- and post- interviews with students and mentors, and follow-up interviews that occurred one year after the course had ended. Quan interviewed nine students across seventeen interviews. Throughout the interview process, Quan was particularly interested in understanding the experiences of students from communities that are not typically represented in physics, for example: women, students of color, transfer students, parents, students from low socioeconomic backgrounds, and first-generation college students.

Within this paper, we only draw from three interviews of a single student, Cassandra. The first occurred four weeks into her 299B research project (t_1), the second occurred immediately after 299B ended (t_2), and the third occurred one year after the 299B project ended (t_3). Interviews were semi-structured; the protocol (shown in Appendix B) loosely directed the conversation and the interviewer pursued in more detail ideas and experiences that were most salient to students. Interview topics included students' attitudes toward their research project, students' sense of belonging within the physics major, and what they felt like they were getting out of doing research. In the t_2 and t_3 interviews, the interviewer also followed up with students on themes discussed in the first interview.

We selected Cassandra as the focus for this study because in many ways, Cassandra's experience in the physics department at the University of Maryland is unique. As a woman who is a transfer student, and several years older than most undergraduate students, Cassandra experienced multiple forms of marginalization and unique external pressures. (We note, however, that Cassandra was not the only student in the data set who was an older transfer student). At the same time, Cassandra drew on relationships in several physics settings to ultimately find community membership. We see these dramatic shifts in her belonging over time, and her continued persistence through challenges, as illustrative of many of the challenges that students from nondominant communities face in physics. Her successes also point to several entry points that were consequential for her increased access to physics. We find the case of Cassandra especially important to understand if our goal is to understand how students from nondominant backgrounds can find entry points into physics; we have a lot to learn from case studies in which the student is marginalized in multiple interacting ways but nonetheless finds multiple entry points. Additionally, from a moral perspective, these "outlier" cases are often the students who are most at risk of dropping out, and thus the students we should care the most to understand [185].

5.4.3 Person-centered ethnographic approach

We develop a person-centered ethnography to tell the story of Cassandra. Ethnography, a methodology rooted in anthropology, involves the study of cultures with researchers embedded within those cultures [82]. A wide set of ethnographic studies of undergraduate STEM fields has revealed important aspects of STEM culture, such as cultural norms that lead to student attrition and how race and gender impact students in being recognized as scientists [5, 7, 33].

Person-centered ethnography (or "ethnography of the particular") is an in-depth study of individuals within those cultures [3, 37, 83], which foregrounds the unique aspects of an individual's experience as they move through a culture. As Foor, Walden, and Trytten describe, "This approach does not examine the institutional politics for themselves but rather the effects of these politics on everyday life and the ways power is experienced by an individual" [37]. Stevens, O'Connor and Garrison argue that such a lens can illustrate how small, sometimes idiosyncratic, experiences can have a cascading effect in students' broader trajectories [3]. Averaging across student experiences and identifying which variables lead to their persistence and attrition can miss these small, but consequential events.

Studying culture through the lens of a single person can be particularly insightful to understanding how marginalized students interact with sociocultural forces. Often in studies of underrepresented students, researchers aggregate demographic categories and look for "gaps" between majority and minority groups. This implicitly treats the white male student as the "norm," and can reproduce harmful narratives about certain groups of students as "failing" or "behind" [4, 183, 186]. In contrast, a small-N approach can illustrate the different ways that people contest these narratives [183] and the resources they draw on to be successful [30, 187]. As Slaton and Pawley describe, aggregating students into "tidy categories" not only risks essentializing students, but fails to account for how the overlap of such categories intersect in unique ways [4].

5.4.4 Analysis

After collecting the pre- (t_1) and post- (t_2) interviews, Quan developed content logs [134] which described main themes of each interview. Because we were interested in students' participation in the physics community, Quan flagged moments in which students positioned themselves relative to the discipline (e.g., "I'm a theory person") or practices of the discipline ("I learned to not be afraid of coding"). Throughout this process, several themes emerged across interviews with multiple students, such as how students' sense of belonging with peers, students' relationships with mentors, and aspects of students' personal histories that impacted the way they interacted with peers or research mentors. During this process, we iteratively moved between themes which emerged in data and themes from the literature to refine our foci. Quan narrowed her analysis to several focal cases, which were selected based on being outlier cases and/or students who were illustrative examples of inbound or outbound trajectories relative to the physics community. Three of these focal students were invited to participate in a follow-up interview (t_3), and the analytic process was repeated. We then selected Cassandra as the focus of this analysis for the reasons outlined in the previous section.

After refining categories, we fully transcribed the interviews and narrowed the focus of analysis to Cassandra's relationships with peers and research mentors. We then developed analytic memos in which we used transcript segments to develop claims [134, 136] about Cassandra's personal identity, her perception of normative identities in physics, and the relationships between Cassandra's personal and normative identity. In order to characterize normative identities, we looked for moments where Cassandra described expectations of others (e.g., “they assume I’m near their age group”) or common behaviors of her physics peers. For example, saying “it’s pretty acceptable at this school to just like walk into professors’ offices and start talking to them” suggests that the normative identity for physics students includes initiating conversations with faculty in their offices. Normative identities also captures the roles and positions that Cassandra ascribes to women. For example, saying that women have to either “be one of the guys or...be a lone wolf” indicates that she sees two normative identities for women, either as behaving like the men or isolating oneself.

We analyzed for Cassandra’s personal identity by looking for reflections of how she sees herself (e.g., “I’ve become more outgoing”) or her perceptions of how others see her. Personal identities also frequently were described in relation to normative identities. For example, when Cassandra describes “I was raised to give people space who are above you,” this reflects an aspect of Cassandra’s personal history that was in tension with the normative identity of knocking on faculty’s office doors.

Similar to Cobb et al.’s analysis, we studied how Cassandra’s personal identity related to normative identities and the level of discord or harmony between them [42]. The level of alignment between personal and normative identities was identified by Cassandra explicitly drawing connections between the two. For example, “I’m just as bad and just as good as everybody else... everybody’s struggling,” reflects the fact that her struggles are similar to those of her peers, and that her personal identity aligns with her perception of normative identity within the peer environment.

Within our analyses, we specifically looked for aspects of normative identities related to race, gender, and socioeconomic status, and other dimensions along which students described marginalization. Several interview prompts at the end of t_2 elucidated these aspects, including “Why do you think there is so little gender and racial diversity in physics?” and “Do you think this has had any bearing on your experiences here?” Cassandra also spontaneously commented on aspects of marginalization and belonging throughout all three interviews. We identified themes connected to Cassandra’s gender, socioeconomic status, transfer student status, and age. We analyzed for racial identity, but Cassandra did not discuss race as connected to personally meaningful stories in physics. In our other case studies, white students and students of color described the racialized nature of doing physics. While we do not analyze for race in this paper, we see it as an important area of study in future case studies.

We then analyzed for how personal identity, normative identity, and the relationship between the two evolved over time.

Figure 5.1 depicts our foci for analysis. Longitudinal analysis of normative identities (N_1 to N_2) were identified by changes or continuity in how Cassandra described what it means to be good at physics, and the roles that were available in the physics community. Similarly, we analyzed for changes and continuity in personal identity (P_1 to P_2). For example, Cassandra described becoming more outgoing between P_1 and P_3. And as both of these changed, we looked for changes in the level of alignment/harmony or discord/misalignment between P and N. We

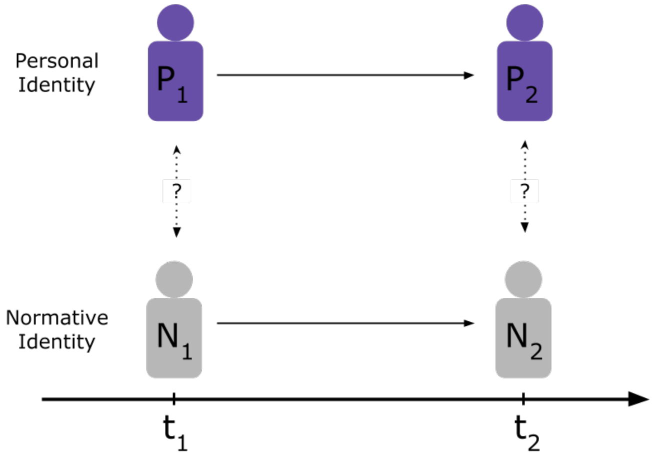

Figure 5.1: Timeline of shifts in personal and normative identity. Time is represented on horizontal axis. Personal identities are purple and normative identities are gray.

now elaborate on how we characterized changes and continuity.

5.4.4.1 Past, present and future analyses

While conducting interviews, we used what Stevens et al. refer to as a past, present and future approach, which involves asking participants to reflect on the past, describe their current state, and project into the future [3]. This approach allows us to see continuity and variation over time in how students make sense of their experiences.

Across the three interviews, we looked for *continuity, recontextualization,* and *shifts* in interaction patterns to understand shifts in normative and personal identities. *Continuity* refers to similar descriptions of the same identity or identity building resource. A student might consistently describe a scholarship program as helping her feel like part of a community. The continuity across accounts would strengthen the argument that the program was consequential. *Recontextualization* refers to how a student's interpretation of a single event changes over time. For example, a student might describe wondering whether he wants to stay in physics after doing poorly in a physics lab course, but later recontextualize doing poorly in the lab course as not being indicative of his ability to do physics research after learning more about the nature of physics research. Analyzing for recontextualization looks for changes in how students are making sense of their experiences and their relationship to physics. *Shifts in interaction patterns* are differences in interaction patterns between students and other physics community members at different points in time. A student saying at t_1 that he never talks to physics majors and at

t_2 saying he regularly studies with other physics majors would reveal a shift in how the student interacts with peers.

5.5 Positionality

This section is written from the perspective of Quan, who conducted the majority of the analysis on Cassandra.

Before sharing my analyses, I will explore my relationship to participants in the study and how it impacted the forms of data collected and my choice of analyses. As researchers, our choices of what to study and how we study it are informed by our identities and histories, and it is important to consider how this impacts our findings [188, 189]. Even my choice to foreground how marginalized aspects of students' identities is informed by my own personal motivations to increase inclusiveness in physics.

I am in the same physics department as students in this study, and I play an active role in departmental activities beyond the research project. I received my undergraduate degree from the University of California, Berkeley, which is similar to Maryland's physics department in terms of size, amount of research, and prestige. While I was not an instructor of the course in the focal year, I co-developed and co-taught the course the two years prior. During the focal year, I attended course planning meetings and every seminar session. My role was described to students as a researcher of the course, but I participated occasionally during course activities. I also occasionally gave feedback and asked probing questions to students during group work activities. Before and after course meetings, I would occasionally talk to students about their school-related experiences and personal life.

Participating in the same classroom and department community as students afforded some degree of shared meaning between participants and I that informed my research interpretations. During interviews, students would often reference aspects of the course, other courses in the department, or people within the department. As a person who has taken advanced coursework in physics and has close friendships with other researchers, my knowledge of physics also supported my analyses and likely impacted how students chose to talk about their research with me.

I also had more extended interactions with several students, including Cassandra, outside of the interview setting. She would occasionally stop by my office to discuss aspects of physics and personal life. I was a guest instructor for two sessions of the S-STEM course when Cassandra was taking it. While these interactions are not written into the analyses in this paper, these inevitably informed my overall sense of her identity trajectory and supported my interpretations of her narratives.

My proximity to the classroom and departmental community also has limitations. Because I was not an outsider, students may have given more positive accounts of their experience in the course, or chosen to hide information that would have portrayed the course in a negative light. We did find that students willingly shared criticisms of the course, which suggests that they were not simply telling me what I wanted to hear. It is plausible that in a more anonymous setting, students would have shared more vulnerable information about themselves or more open critique of the course.

I am a cisgendered heterosexual Asian-American female. These aspects of my identity also likely impacted the kinds of personal experiences that students shared in interviews. In several cases, white women and students of color openly expressed discrimination in the department. While I did not explicitly share my personal experiences with discrimination with them, I believe that being an Asian woman contributed to assumed familiarity with such experiences. As an Asian female, I am also more likely to be perceived by others as unthreatening. Had the interviews been conducted by a white man, students may have had less comfort in sharing such experiences.

5.6 Results

We now present analyses of several threads that illustrate shifts and continuity in Cassandra's identity within the physics community of practice. We first present about Cassandra's relationships to peers in peer environments, foregrounding her experiences with objectification of women in the department, and shifts in what it means to do physics competently. We then present one thread about her relationship with her research mentor in her research experience, focusing on the ways that students and faculty work together. In each thread, we describe the normative identity at a given time (N_t), Cassandra's personal identity (P_t), and the relationship between them (relating N_t and P_t).

5.7 Cassandra's Relationship to Peers

5.7.1 Objectification of Women

Throughout Cassandra's interviews, she described gendered interactions between herself and other male students in the department. One common theme in Cassandra's interviews is how Cassandra dealt with unwanted objectification from male undergraduate students.

5.7.1.1 t_1

At t_1, Cassandra's experience with objectification is also heightened by her age. She describes how the objectification of men, in addition to being older than her peers, impacted a lack of sense of belonging in the department:

> Interviewer: Um, so would you say that like, in this physics department, you sort of feel connected to your peers?
> Cassandra: Yes and no connected. Yes because we're, like I said, we're all in the same boat. We're all really interested in the same stuff, but because I'm a lot older, it can get a little weird. (Laughing) It can, especially cause a lot of these umm- a lot of other physics students are

	Personal Identity	Normative Identity
t_1	Older woman, not romantically interested in receiving male attention, preferring to hang out with women.	Men objectify women.
t_3	Woman who can manage the unwanted male attention. Uses age to scare people off.	Women hide in the corner, men still objectify women.

Table 5.1: Cassandra's normative and personal identity at t_1 and t_3 with respect to peer objectification.

> boys and, and so, I prefer to geek out with other girls. if a young man approaches me to start up a conversation, I always feel obligated to be like, I'm married. I don't know cause, sometimes they don't know, you know? So I don't know, it just makes it odd. So I don't know, it's a weird dynamic (putting hands in face) But yeah I do feel like I'm around people that I belong and I really enjoy talking to them but at the same time it's still a little distant. Just because I'm in like another world, like I don't know, I'm in another ladder of society.

In this quote, Cassandra points out her age and her gender as contributing factors to isolation. She brings up unwanted male attention from younger men in the department approaching her, which she feels "obligated" to deflect. Her descriptions of herself reflect a strong sense of otherness; she describes herself as "in another world" and "in another ladder of society." This otherness stemming from her age and gender suggest that the normative physics identity involves being male and late teens/early twenties. Cassandra elaborates on this "weird dynamic" and how she has to navigate the challenge of unwanted attention:

> A lot of the times they'll assume like you're near their age group. I had one kid that like tried to date me...I don't know if I sound sexist like saying I just want to hang out with the girls, but, (shrugs) it's just easier that way. I get approached a lot actually by these young boys...it's really awkward cause I want to have friends, you know? Like I want to just talk to people, and be a person. I don't think they're used to, they don't see a lot of girls, you know? So they'll cling to girls. I don't mind conversing with them, and having conversation, and then something happens where they start to get a little like "Oooh, you want my phone number? You want to hang out?"... When I tell them how old I am, one even told me that I just ruined his whole day... I was like "Whaaat?"...they totally alienate me, they alienate me the second they find how old I am. Most- I mean not all of them. But that's why in class I try to announce it, like "hey I'm married, Yeah, I'm old, I'm a old lady. Like if you need some advice let me know" I try to like keep that but if I don't get the

> chance to announce it to the class, then it's I don't know, it becomes a very strange experience.

Cassandra describes the challenge of wanting to have friends, which she poignantly states "I just want to talk to people, and be a person." But because of the unwanted romantic attention, and backlash when she rejects this attention, she is alienated. At the end of this excerpt, Cassandra describes announcing up front her age and marital status, to preempt any "outing" later, and having people find out on her own terms. As Cassandra states, her peers would otherwise assume that she was younger and unmarried; Cassandra's personal identity as an older and married misaligns with the normative physics identity of being young and single.

$\underline{N_1}$: Cassandra descriptions of unwanted male attention reflect how it is normative for men in the department to objectify women. Cassandra describes these men as "clinging" to women in the department because women are so uncommon, suggesting receiving unwanted attention is a common experience for women in the department. Cassandra is assumed to be younger than she is, suggesting that the normative identity is to be late teens/early twenties.

$\underline{P_1}$: Cassandra describes herself as being an older woman who is not interested in objectification from "boys." For this reason, she would rather hang out with other female physics majors.

$\underline{\text{Relationship between } N_1 \text{ and } P_1}$: Cassandra's desire to not be objectified is at odds with the normalization of objectification from male peers. Cassandra manages this tension in a couple of ways: 1) She prefers to hang out with other women and 2) She announces to others that she's older and married, making sure she is "found out" on her own terms. This tension makes Cassandra feel like she can't "be a person" and "have friends."

5.7.1.2 t_3

At t_3, Cassandra describes having a greater sense of confidence in her physics ability, and is more outgoing about making new friends in the department (this will be elaborated on in the next subsection). At the end of the t_3 interview, the interviewer asked her to comment again on her experience as a woman in the department. Cassandra starts by describing some of the same kinds of feelings of loneliness and isolation, but she experiences those feelings to a lesser extent than before. She also describes how her approach toward being objectified has shifted:

> Interviewer: Yeah, so I guess, um, I'm wondering if you could comment on on what you think it's like, what it's like for you to be a woman in this department.
> Cassandra: ...I don't feel like I have to hide in the corner anymore. I feel capable if somebody oversteps their bounds that I can just like shut them down and be fine. Plus like, I'm older, like, I don't think a lot of these young men know how old I am. And so um, I can just scare them with my age and it's okay. But, but like it's, it's nice being able to just

> talk to people not hiding... that, I think, made it harder for me to evolve and do well. Like now I don't feel that so I'm not as stressed out.

When Cassandra describes "if somebody oversteps their bounds," she seems to be referring to receiving unwanted male attention. She describes now being able to "shut them down" instead of "hide in the corner" which suggests a change in her personal identity. Her use of the word "evolve" suggests that she also perceives being different than she was before. Her age, which in P_1 was a source of isolation and otherness can now be used to "scare them away." While Cassandra's personal identity shifts, male objectification is still present in N_3. Cassandra describes a situation:

> At the end of the class, this one guy came up to me and he was like, "yeah, I heard you sounded frustrated like you didn't understand what he was doing but this is what he was doing." And I'm like, "I know what he was doing." He was just talking to me that was, like, almost belittling, like "oh how cute, let me help you," but also, like, flirtatious. And I was just like, "What?" He thought it was his in to talk to me... No, dude. I get what's going on. If there were other people in the class, you probably wouldn't have gone up to them, but since I'm a girl you feel like you're entitled to come and like grace me with your intelligence... I think when I shut him down I like, burned him with my gaze, (laughs) cause he disappeared when I was like, "I GOT IT."

In this situation, Cassandra describes being similarly objectified as in t_1, but her approach to dealing with this is different. She "shuts him down" with her "gaze" and asserting that she's "got it." Throughout Cassandra's narration of this interaction, there's a strong sense of pride and confidence in her own physics ability, and pride in being able to shut down her peer's advances. This is markedly different from Cassandra's reactions toward being objectified in t_1; she now has a stronger sense of agency in managing these interactions.

Cassandra uses her prior personal identity P_1 to interpret the behaviors of other women in her classes:

> Cassandra: ...I think I've become more approachable this semester cause more people are talking to me cause I'm not like scowling at everybody now. So I don't know, like some girls I see in class have that look that I used to have, like don't look at me, I'm keeping my head down, I'm sitting in the corner. If you look at me, I'm gonna destroy you with my eyes, you know? And so, I am afraid to go talk to those girls. Cause they don't look like they wanna be talked to, and I get it cause I was that, I didn't wanna be talked to either... I don't do that anymore in my classes. I, like, sit like really open, like I do, I have my, like, feet up, I'm just like, yeah. I'll make eye contact with people and like, nod. And they'll, like, wanna talk to me because of it. You know? And so, I'm very much more approachable...I mean you're in a room with just boys.

> You don't wanna be objectified. It's it's easier to just be defensive and just stick to what you're doing and not think about anything else.

Cassandra describes how it's common for some women to "sit in the corner" and scare people away. She attributed this as a defense mechanism to avoid being objectified, which she infers based on her prior experiences (P_1). Cassandra's comment that women have a look that says "I'm gonna destroy you with my eyes," echoes the experience with the male student at t_3, where she "burned him" with her "gaze," but this is a tool that she now uses more strategically and sparingly compared to before. Cassandra's descriptions of other women at t_3 illustrate the shift from P_1 and P_3; Cassandra's personal identity is more open and involves fostering more connections with people.

$\underline{N_3}$: Cassandra's continued descriptions of being objectified and other women's avoidance of male attention suggests that there is continuity across N_1 and N_3 in terms of the objectification of women.

$\underline{P_3}$: Cassandra describes herself as confident that she can "shut people down" and deal with unwanted behaviors in an agentive way. This is tied to her growing sense of confidence in her own abilities and belonging in the department.

Relation between N_3 and P_3: Cassandra's desire to not be objectified is still in tension with the continued objectification of women. But she now sees herself as managing this tension differently. Before, she would "hide in the corner," but now she can be more outgoing and shut people down.

5.7.1.3 Discussion

In both t_1 and t_3, there is continuity in the normative physics identity of objectifying women in the department. The aspects of Cassandra's personal identity which are most salient at t_1 and t_3 are partly a result of these normative identities. Cassandra's initial personal identity P_1 is characterized by being older and uninterested in male attention. P_1 and N_1 are in tension with one another and lead to Cassandra avoiding interactions with male peers and volunteering information about her age and marital status to avoid being "found out." Cassandra's later personal identity, P_3 is characterized by being outgoing and able to "shut people down."

An important aspect of Cassandra's experience is that even though her personal identity shifts and she finds greater sense of belonging in physics, she still has to manage unwanted male attention. And while she seems to feel better about how she manages this attention, it still is an additional emotional burden she has to deal with in physics spaces.

5.7.2 Sense of what it means to do physics competently

Another thread in Cassandra's experience is her shifting sense of what it means to be good at physics and how one demonstrates being good at physics. This is paired with her growing sense of competence in physics. In Cassandra's case, doing physics competently was interwoven with how she talked about her sense of belonging with peers.

In this section, I focus on what being good at physics means with respect to coursework, since this is fairly different than what being good at physics research means to Cassandra.

	Personal Identity	Normative Identity
t_1	Looks for simplest way to understand things. Sees this as "dumbing down"	Want to tell you the "nuance" of what's happening
t_2	"Carries on" with challenges.	Girls quit when there's the threat of not doing well on exams. Girls are either "outstanding" or "shrinking violets."
t_3	Sees herself as "just as good and just as bad" as everyone else. Was the only person to solve a hard math problem. Cassandra goes out of her way to talk to others.	Everyone has strengths and weaknesses. Competence demonstrated by performing. Physics majors can be non-social and reserved.

Table 5.2: Cassandra's normative and personal identity at t_1, t_2, and t_3 related to what it means to be good at physics in peer settings.

5.7.2.1 t_1

At t_1, Cassandra only describes one interaction with peers that center around doing physics. In this interaction, Cassandra is being tutored at the Society of Physics Students (SPS) tutoring by a more senior student. Cassandra describes a disconnect between the way that concepts were explained to her in SPS and her courses, and attributes it to not being smart enough to understand them:

> Cassandra: I did try the physics tutoring. I don't know if you know-
> Interviewer: From SPS?
> Cassandra: Yeah the 4 to 6 [PM] tutoring, but that didn't, that didn't help me very much. It kinda overcomplicated some of the things. I noticed when I get help from people who are way smarter than me, they make me, I don't know how to explain it, like if I'm, I like to look for the simplest way to do things, and usually people who have a lot more knowledge will wanna tell you every awesome nuance of everything you're doing. Which is cool if I'm not studying for an exam, if I need to know something to know it to take an exam, it really doesn't help. So like, for my E&M exam, there are like, like our teacher told us there's a way to calculate the electric field without integrating and when I went in for help, I was like "ok, he told me to do this without integrating" and they're like, "no, you need to do triple integral, you need to integrate θ, ϕ, r all that stuff." And I was like, "Oh, god ok." And I was trying so hard to get down these triple integrals and the exam comes and I know I did awful, and after the exam, one of the kids in my class was

> like, “no it’s just the area over such and such” and I was like, “what?” So it doesn’t always help when people are so smart and I respect their intelligence, I think they’re amazing. But I don’t know, I need it to be dumbed down. I need someone on my level to study with.

In this example, Cassandra describes trying to calculate electric fields in an E&M course, and struggling when the tutor tells her to use integrals instead of Gauss’s Law. In her narration, the tutor explicitly tells her to use the complicated integration instead of what her professor had told her to use, and what she had been expected to use on the exam. Cassandra attributes her confusion in understanding the tutor’s help to them being “way smarter” than her and not “on her level.” For the purposes of the exam, she would rather have it “dumbed down (although she suggests that she would be okay with the detail if she hadn’t been studying). Another person might interpret the tutor as making the problems unnecessarily complicated (and a reflection of the tutor’s lack of awareness of where Cassandra is at), but Cassandra frames them as wanting to tell her “every awesome nuance of everything.”

$\underline{N_1}$: The upper level physics majors at tutoring solve problems in overly complicated ways. Cassandra sees this as a them being “so smart.”

$\underline{P_1}$: In the context of exam studying, Cassandra sees herself as needing material to be “dumbed down” and prefers simple ways of solving problems.

$\underline{\text{Relating } N_1 \text{ and } P_1}$: There was a disconnect between how Cassandra wanted to go about solving the problem and the tutor’s explanations. Cassandra attributed this to the tutor being “way smarter” than her.

5.7.2.2 t_2:

At t_2, Cassandra also does not have much description of doing physics with other physics majors. She does describe how in the semester in which 299B occurred, she had a graduate student tutor who was “awesome,” and she feels differently about SPS tutoring:

> Interviewer: Do you feel a sense of community in physics department?
> ...
> Cassandra: Yes. at first I didn’t. Um, but when I started getting more involved, like I had a tutor last semester and he was awesome, a grad student. And getting to know him and learning, getting to know the different people that are doing physics and seeing the array of different personalities and types, and like minds, it made me feel like there’s a sense of community... I went to the tutoring room last semester and I got to know a couple of the higher level physics students. And I felt like there’s community among them. And they relied on each other and they’re friends. And I always feel welcome when I hang out in the physics students lounge. And you can just hang out there and you’re part of the group, everybody feels like they’re of some like mind, although it’s probably not true.

Cassandra doesn't describe the same sense of otherness as we saw in t_1. In this interview, the tutoring room is recontextualized as a place where she feels a sense of community, and where she gets to know more senior physics students. She had been prompted to describe her sense of community, so it is also plausible that the question didn't queue similar feelings toward her competency in physics.

When asked about lack of gender representation in the department, Cassandra describes how experiencing challenging physics can be threatening to women:

> Interviewer: Why do you think there are so few women in this department? Or in physics in general?
> Cassandra: I noticed one thing, from my last class, my physics professor last semester was awful... I noticed that half the class dropped after the first exam. Of all the girls, there were only 2 of us left. So I noticed that like, and I'm the same way, is that, like when there's a threat of not doing well, a lot of girls quit. Cause they wanna be seen as on the level of the guys. This is speculation, okay, I can't speak for all women, um, but I noticed that all the girls were gone except for me and another girl. But me and this other girl are in like every class together. So she's, maybe more like me as far as you know, I'm gonna carry on, like screw this, like I don't care, I got my first C, okay so what? It's not gonna kill my GPA, and I probably won't get another C ever again. But it didn't- the other girls seemed like so afraid of being not as well- as good as everybody else, like they'd rather drop the class and retake it. Because it's almost like you have something to prove. And maybe that's why there aren't as many women in this department...it does kinda feel like a boys club in a way, cause when I got to tutoring like they're all boys, they're all hanging out, they're all friends. There's a couple of like, outstanding girls, but those girls, they either have huge personalities or they're kinda like shrinking violets. You know? There's like no, just like girls being themselves. Maybe there are and I just don't meet them. But, from what I've seen is that you have to like, be a part of it and be one of the guys or like separate yourself and like, be a lone wolf. You can't just be, you know?

In this example, Cassandra describes how doing well in the course is tied to exam and course grades. To her, this is gendered; women are more likely to quit when there's the threat of receiving a bad grade, since women "have something to prove." Cassandra describes herself (and another outlier woman) as being different from the typical woman in this class, because they're willing to accept getting a C in a course.

Cassandra's description of women feeling threatened by bad grades seamlessly ties into her descriptions of the gendered nature of belonging in physics settings. Cassandra describes women as having two options for participation, being "outstanding"/"one of the guys" or "shrinking violets"/"a lone wolf." This aligns with other work in undergraduate computer science [7] and engineering [33] which has illustrated how women are limited to a few ways of "being" in a domain, whereas men tend to have a broader set of identities available to them.

$\underline{N_2}$: Cassandra describes a norm of women quitting courses when there's the threat of not doing well. Doing well in physics means getting high grades on exams and final grades. Women are also limited in the kinds of roles they take on, either "outstanding" or "shrinking violets."

$\underline{P_2}$: Cassandra portrays herself as someone who is willing to deal with poor grades, and less afraid of poor grades than other women.

$\underline{\text{Relation between } N_2 \text{ and } P_2}$: Cassandra describes herself (and another woman) as being different from other women in physics because they're willing to accept bad grades. Cassandra and this other woman still experience the same threat of doing poorly in this class. Cassandra is not explicit about whether she sees herself as one of the "outstanding" women or a "shrinking violet" or someone else.

5.7.2.3 t_3

At t_3, Cassandra starts to see "being good" at physics in more multifaceted ways. She has the sense that her peers have strengths and weaknesses (like her) and has a greater sense of belonging.

> Cassandra: This is the first semester where I've felt like I belonged in physics. Like, I didn't feel like an outsider or like oh, I'm not as good as everybody else, you now? This semester I started to realize that I'm just as bad and just as good as everybody else... I think it was getting to know some of my classmates, finally. Now that I'm getting to know more people, I'm realizing that everybody's struggling. We are all kinda in this thing together and then, like. Some things that I know and they don't know and vice versa. And so, it just made me feel that I was at the level of everybody else. And like um, and like in my math class there's this one problem that the teacher assigned for homework and the teacher couldn't even do it but like, I had done it and I guess I was the only one in class who was able to do it and he used my answer as the solution on the website. And it felt good, like wow, like, I can do some of this stuff, like, legitimately.

Instead of seeing "smart" dichotomously as in previous interviews, Cassandra describes coming to understand that her peers have strengths and gaps in knowledge, just as she does. Her wording, "just as bad and just as good," suggests that these two qualities now coexist for her. In Cassandra's narrative, this stems from getting to know her classmates better, and seeing them as more multifaceted people. We also see greater affiliation with other physics majors when she says, "we are all kinda in this thing together."

Cassandra then elaborates on one moment that demonstrates her competence, where she solved a homework problem that none of her classmates nor her instructor could solve. To her, this moment contributed to her sense that she can do physics "legitimately."

The interviewer asked Cassandra to elaborate on how she was able to meet other physics majors. She began by talking about the S-STEM course, a small scholarship program in the department that focuses on building community and doing physics together (299B is a component of the S-STEM program, but the course that Cassandra is referring to is a different seminar). After meeting students through S-STEM classmates, Cassandra went out of her way to study with other physics majors in the Toll Room, an open room in the Toll physics building where students tend to gather to study.

> Interviewer: So where, so you mentioned like meeting more of your classmates, like is that happening in class or in other spaces?
> Cassandra: Yeah, well I guess the S-STEM [Focus on Physics] class helped somewhat because -like um, [Classmate] is in a couple of my classes and um, like, I always have been smiley with him in class, cause you know some people are awkward and some people like look at you and smile when you look at them, so he was one of those people... I was like oh hey we're in classes together, like we've acknowledged each other's existence before, and so he was easy to talk to, and then talking to him, you know I met other people I talked to. I don't know it kinda started to trickle down. Or like I'd run into people in like the Toll Room [open studying room] studying for the same thing, so I met another person that way. Like, "hey look, we're doing the same thing, come over here, let's do homework together" and the guy was like, "yeah! that's a great idea," and he understood some quantum computing stuff and I understood like some integral that he didn't know how to do. So that like, getting to talk to people and like share your strengths together, like I don't know, I've just become more outgoing like forcing people to talk to me. (Laughs) It works sometimes.

Cassandra describes some physics majors as being "awkward," while others are more like the student in her S-STEM course. After getting to make friends through him, she says that meeting peers "started to trickle down." She then narrates an instance in which she went out of her way to study with another student in the Toll Room. In this studying example, Cassandra brought her own unique strengths to the group (understanding an integral) as did the other student (understanding quantum computing). This distributed expertise echoes the "just as bad and just as good" from earlier in the interview.

$\underline{N_3}$: Cassandra has a multifaceted view of "being good" at physics, in which everyone has strengths and weaknesses. Competence is still demonstrated by succeeding at a task or problem. Cassandra also describes physics majors as being both reserved or friendly.

$\underline{P_3}$: Cassandra sees herself as "just as good and just as bad" as everyone else. She has also demonstrated some competence by being the only person to solve a hard math problem. She is now more outgoing, going out of her way to talk to others.

$\underline{\text{Relating } N_3 \text{ and } P_3}$: There's greater alignment between Cassandra's personal identity and her perceived normative identity, now that the normative identity of being good at physics is more multifaceted. There's still some continuity in seeing "good at physics" as being able to successfully complete a task or problem, but now Cassandra has a concrete example of her achieving a task that nobody else was able to complete. This greater sense that Cassandra's personal identity aligns with the normative identity is also paired with Cassandra being more outgoing toward other physics majors.

5.7.2.4 Discussion

Cassandra describes coming to see competency among physics students in a multifaceted way, instead of seeing students as either good or bad. She also gains a concrete example of herself performing physics competently when she solves a difficult problem in one of her classes. These shifts in personal and normative identity contribute to greater harmony between her personal identity and normative identity, and an increased sense of belonging. One contributor to Cassandra's expanded notion of competency is having the opportunity to meet and work with other majors more closely, through friends and tutors. As Cassandra's interactions with other physics majors increase, she also is friendly and outgoing toward other physics majors.

Cassandra's sense of belonging increased through coming to see physics majors as more nuanced people, and seeing a multiplicity of ways to be "good" at physics. This is aligned with work by Cohen [17], which emphasizes the unique strengths that individuals bring to challenging tasks. We find it noteworthy that the opportunities that led to Cassandra's increased interactions with peers happened in non-traditional spaces. Tutoring and the student lounge are both spaces that are run by students. The S-STEM program is a small, extracurricular scholarship program which promotes community building and discussions. This points to the importance of creating opportunities outside of traditional coursework for students to engage with one another.

5.8 Shifts in Relationship to research advisor

We found continuity in Cassandra's description of 299B giving her the opportunity to work with her research mentor, which she felt like she would not have gotten otherwise. Their interactions shifted over time; Cassandra and her mentor initially met infrequently and communicated via email, but at t_3 they met weekly. Finally, we see Cassandra's *recontexutalization* of their initially infrequent meetings, which at t_3, Cassandra reinterpreted as to "proving" herself as a serious and committed researcher. We note that in this section, we stay close to Cassandra's interpretations of events. In the discussion section, we elaborate on the implications of the meritocratic narrative.

5.8.1 Ways of working in physics

	Personal Identity	Normative Identity
t_1	Giving people space that are above you.	Acceptable to knock on doors.
t_2	Forcing him to meet with her/ answer her questions. Dissatisfaction with unanswered questions.	Physicists are introverts. Hard to get time with mentor/ unresponsive to email
t_3	Committed/ demonstrates persistence/ grit.	Old timers judge people as flaky or committed and invest their time in students that demonstrate their commitment.

Table 5.3: Cassandra's normative and personal identity at t_1, t_2, and t_3 related to how students interact with faculty.

5.8.1.1 t_1

At t_1, Cassandra describes a history of wanting to meet her mentor before the course, but feeling unable to do so:

> Cassandra: I was really most excited about meeting [Mentor]. Because he's the college cosmologist and he's been on my radar for like, a while. And like, I'm gonna meet him one day. So I was really excited about that and I really wanna impress him.
> Interviewer: When did you find out about him?
> Cassandra: I found out about him the beginning of last semester when I was talking to my astro professor, and he was like, you need to meet such and such, [Mentor], and I was like, 'oh? really?' And he was going on about how you should just walk in but I don't know I got nervous about just walking in and talking to him, so I didn't find another way to...I guess cause it's pretty acceptable at this school to just like walk into professors' offices and start talking to them and I didn't really know that. I think I was kinda raised to think that you give people space that are above you and I don't know. I feel like sometimes I, like I don't give myself enough credit, you know where like I'm not smart enough to go and talk to someone like that I don't know what it is. But it made me kinda nervous to go in there and strike up a conversation.

In this statement, Cassandra describes the sense of anticipation she had leading up to meeting her mentor, and positions him as an expert who is "above" her in status. Cassandra then describes an instance in which another professor tells her to go meet her mentor, but she hesitates and doesn't do it. Cassandra attributes this in part to being "raised to think that you give people space that are above you." Her experience reveals how one of the physics norms of knocking on doors was in tension with Cassandra's personal identity. Though she was told by others that it is okay to do that, it didn't take away the discomfort of doing that.

$\underline{P_1}$: Cassandra describes not seeking out research on her own because she was "raised to give space" to people who are above her. Her personal identity involves seeing herself as "below" faculty in status.

$\underline{N_1}$: Cassandra describes that it is acceptable to "knock on doors" and ask about someone's research.

Relating P_1 and N_1: There's a strong sense of discord between what Cassandra knows is acceptable within physics (knocking on doors) and her descriptions of her upbringing. Even when she is told that she should knock on doors to ask for research, this is still in tension with P_1, so Cassandra resists N_1.

5.8.1.2 t_2

At the t_2 interview, Cassandra reiterates that she had wanted to work with her mentor prior to taking 299B, and the course gave her that opportunity.

> Interviewer: Um. so what was the experience of like getting started in this project like for you?
> Cassandra: ...I've been waiting for this for a couple of semesters and I've been like reading up on the mentor that I have, like waiting for my opportunity to work for him. So it was kinda like things just fell into place.

Cassandra describes this experience as an "opportunity to work for" her mentor. Her use of the word "waiting" and "things just fell into place" positions herself in a passive role with respect to starting this relationship; there wasn't space for her to initiate this relationship on her own.

But despite Cassandra positioning herself passively at the start of her mentoring relationship, she proactively managed their regular meetings:

> Interviewer: So how was- what was your relationship like, with your mentors-
> Cassandra: Umm, Scarce. (Laughs) I don't know, it was very easy to talk to him. Um, we got along pretty well and, it's just he was a busy person and preferred email exchanges. But I kinda forced him to see me anyways. Cause I don't know I just felt email exchanges were impersonal, and I didn't- if I had questions, you know on the fly, you can't really do that through email. But we- we didn't see him often, like maybe every other week...he wasn't a jerk or anything, but he was kind of an introvert. So you know, I had to work around that.

Cassandra describes their relationship as "scarce," because they met "maybe every other week," and communicated via email. She would have rather had more face-to-face time to ask questions. She attributes the impersonal nature of their relationship to being an introvert and being busy.

Cassandra also describes proactively seeking out meetings with her mentor, which she calls "forcing" him to meet with her and "working around" his introverted personality. This "forcing" language comes out several times in this interview. For example, Cassandra later states, "I think forcing him [mentor] to see me more, that probably would have been helpful, and probably like picking his brain more."

$\underline{N_2}$: Cassandra describes her mentor as hard to get time with and unresponsive to email. She refers to him as an "introvert," cueing up ideas that physicists are socially awkward and don't like talking to people.

$\underline{P_2}$: Cassandra positions herself as a person who will be persistent about getting her questions answered. Cassandra also positions herself (in the interview) as a proactive person who "forced" her mentor to see him.

$\underline{\text{Relating } P_2 \text{ and } N_2}$: In some sense, Cassandra was complying with the uncommunicative/introverted N_2. She said she wished she had sought out more time for them to meet, and they weren't able to meet as often as she wanted. At the same time, Cassandra "forcing" her mentor to see her is also one way that she accommodates N_2 in an agentive way. By pushing for more meetings, she had some of her questions answered, and found ways to address the misalignment between N_2 and P_2 by shifting their interactions.

5.8.1.3 t_3

At t_3, Cassandra similarly reiterates this course as giving her the opportunity to work with her mentor, but she now describes the barriers to working with him in a more nuanced way.

> Interviewer: I guess I wonder like do you think that the, if you had done the research experience without the class, like do you think it would have been different?
> Cassandra: Umm, I don't know. I guess um, I probably would have gotten research from whoever had taken me so maybe I wouldn't have done something I wanted to do. Whereas that class let me work with the person I'd been wanting to work with. So it was good... I know [mentor] is hard to approach and usually shuts down people who approach him. And when he does take on people, he's not available to them immediately...So definitely like, I think, let me work with who I wanted to work with.

Again, Cassandra says the "class let me work with the person I'd been wanting to work with." In t_3, however, she elaborates that the class gave her the opportunity because her mentor is "hard to approach." She suggests that this initial unapproachability might have prevented her from working with him without the class.

Cassandra elaborates on her mentor's initial unapproachability:

> Interviewer: Is it challenging to get to be able to sit down with your mentor and like talk face to face?
> Cassandra: No because we schedule once a week. It was when I was in 299B, we had to like find him, or he wouldn't always show up when he said he would, but now he's more invested. Like I think he's the type of guy that people have to prove themselves to, it seems that he gets people that aren't like um, I don't know they're kinda flakey. It seems like some of the grad students he works with, like, I don't know he doesn't talk to them a lot. They're not available, I don't know. So like when he saw that like, "No, I'll be in your face until you work like let me work," I think he realized that like OK she's serious.... I think he could tell that I really wanted to do this. Cause he told me after the 299B class was over that he was like, "look you know, I end up, I try to work with a lot of people and a lot of people just don't seem to get it together." You know? And really push, so he said "I really wanna work with somebody who's gonna stick with this and push and do something" and I was like, "that's me!" And so I think he's had experiences in the past maybe with undergrads so I don't know.

We see some shift in interaction patterns between Cassandra and her mentor. At t_3, they meet "once a week," which is different from the "maybe every other week" meetings Cassandra described at t_2. At t_3, Cassandra also elaborates that during 299B, she and her partner "had to find him" and sometimes he would not show up to their meetings. She now sees him as "more invested."

For Cassandra, her mentor's resistance to in-person meetings, being busy, and "introverted" personality from t_2 is now recontextualized as him being "the type of guy people have to prove themselves to." Cassandra directly attributes his lack of availability at t_2 to being less invested than he is at t_3. Cassandra interprets his lack of investment as stemming from mentees needing to "prove themselves," which is necessary because so many people are "flaky" and can't "get it together."

At t_3, Cassandra recalls seeking out meetings as she described in t_2 (e.g.,"no, I'll be in your face let me work"). But what Cassandra described as "forcing him" to meet with her at t_2 became recontextualized as "proving herself" at t_3. She recontextualizes her persistent requests for meetings and face-to-face time as demonstrating to her mentor that she is a serious and committed person.

$\underline{N_3}$: Cassandra reinterprets the prior unresponsive interactions as her mentoring needing people to prove their commitment, because students can either be flakey or serious. Faculty only invest their time in students who are committed, and it is up to faculty to judge whether a student is committed or not.

$\underline{P_3}$: Cassandra positions herself as the committed, serious kind of researcher that her mentor is looking for. The "forcing" is recontextualized as showing her persistence.

$\underline{\text{Relating } P_3 \text{ and } N_3}$: The normative identity of a successful physicist is one who is persistent, which is aligned with Cassandra's personal identity.

5.8.1.4 Discussion

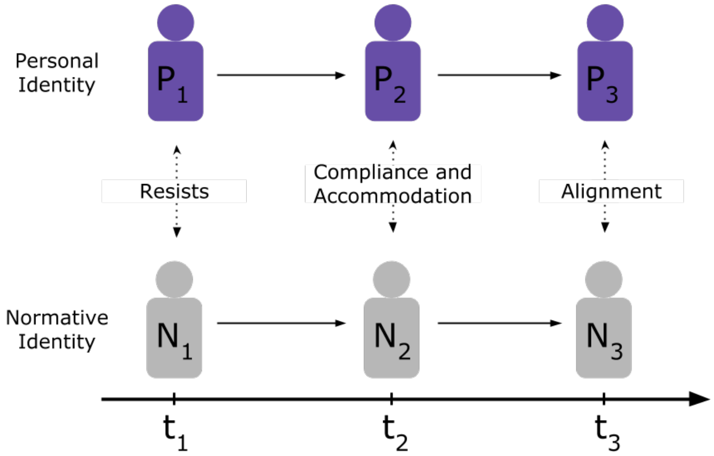

Figure 5.2: Alignment between Cassandra's personal identity and perceived normative identity. At t_1, Cassandra resists the norm that students knock on faculty's doors. At t_2, Cassandra both complies with and accommodates her mentor's working expectations. At t_3, based on shifts in both personal and normative identity, Cassandra aligns herself with the meritocratic idea that students prove themselves to faculty.

Across the three interviews with Cassandra, we identified continuity in how Cassandra saw 299B as an entry point to working with her mentor. We also saw changes in how Cassandra worked with her mentor and changes in how she interpreted their prior working patterns. Cassandra's meetings with her mentor became more frequent after 299B, which she attributed to him becoming "more invested." What she had initially thought of as introversion and resistance to in-person meetings, she recontextualized as her mentor needing students to prove themselves. At t_2, Cassandra saw process of proactively seeking out meetings as "forcing him to see her," but this became recontextualized as "proving herself" as a serious and committed person who was worth her mentor's time.

These changes were also associated with shifts in Cassandra's personal identity and the normative physics identities that she perceived in physics. Cassandra at first "gave space" and saw herself below her mentor, which was in tension with the physics norm of knocking on doors to talk to faculty. She then "forced" her mentor to meet with her, which was one way of accommodating her mentor's introversion. Cassandra then recontextualized this "forcing" as a way to demonstrate commitment to research, and saw her mentor's role as sorting committed students from flakey students. Over time, the relationship between Cassandra's personal identity and normative identity went from being in discord to being in alignment, but this stemmed from both shifts in normative and personal identities.

The continuity of Cassandra seeing the course as giving her opportunities with her mentor suggests that the course is an entry point in to Cassandra's more central participation in physics research. Over time, there are differences in how the entry point functions for Cassandra. In the first interview, she describes how nervousness and wanting to "give space" led her to avoid knocking on his door. By the third interview, she suggests that she might have been shut down by her mentor anyway, had she knocked on his door. This is another entry point which occurred in an nontraditional setting. It may be particularly important for students, as we see in Cassandra's case, to have these well-scaffolded opportunities for engaging in research that are different from the "knocking on doors" approach.

5.9 Discussion

In this paper, we longitudinally analyzed aspects of normative identities and personal identities using narratives from a single case study, Cassandra. We separated our analysis into two categories, shifts in Cassandra's relationships to peers, and shifts in Cassandra's relationships to her research mentor. Overall, shifts in normative and personal identities in both settings led to expanded opportunities for Cassandra's participation in each setting.

Within Cassandra's relationships to peers in peer environments, there is continuity in her experience of being objectified by male students in the department. Over time, her personal identity shifts from avoiding interactions with men to being able to respond to objectification in a more agentive way. Cassandra also experiences shifts in normative identity with respect to what it means to be good at physics. She goes from seeing others as smarter than her to seeing "good" in a more multifaceted way, in which everyone has strengths and weaknesses. These both contribute to (and are fueled by) her greater sense of belonging among peers, and expanded opportunities for participating in physics. We believe that increased interactions with peers and increased affiliation with physics is evidence of Cassandra's greater participation within the physics community, and can likely support future participation.

Within Cassandra's relationship to her mentor, she experiences shifts in how she understands the way that faculty and students work together. At first, while she knows it is acceptable for students to initiate meetings with faculty, this is in tension with her being raised to "give people space." After beginning to work with her mentor, she proactively seeks out more meetings with him, which she interprets as "forcing him" to meet with her. In the final interview, she recontextualizes her mentor's initial unresponsiveness to him needing students to prove themselves to him. She also recontextualizes "forcing" him to meet with her as "proving herself." In seeing herself as having "proved" her commitment and dedication, Cassandra has greater alignment between her personal and normative identities. Across these interviews, Cassandra shifts from blaming herself for not meeting with her mentor (seeing her socialization as holding her back), to seeing her mentor as someone who brushes people away until they demonstrate their commitment.

5.9.1 The importance of non-traditional spaces

There were several entry points that Cassandra described as giving her increased opportunities for participation. While tutoring was initially a place where Cassandra felt marginalized, she later described tutoring as a place where she came to meet other physics majors. Cassandra's participation in the S-STEM scholarship program and course also gave her opportunities to meet other physics majors. These relationships were consequential to Cassandra developing a nuanced sense of what is "good" within physics, and increasing the alignment between her normative and personal identities. Cassandra attributes 299B to giving her the opportunity to meet her mentor, whom she would not otherwise have sought out meetings with, and who might have pushed her away.

These entry points are all non-traditional spaces which exist outside of typical coursework, but support Cassandra in engaging with typical coursework. Both the S-STEM program and 299B explicitly seek to build community among students. The case of Cassandra suggest that these outside spaces, which provide scaffolded opportunities for students to interact with faculty and each other, can play a critical role in growing students' participation within the discipline.

Non-traditional spaces can take many forms. For example, *counterspaces* explicitly combat the harsh cultural norms, microaggressive behavior, and isolation experienced by women of color and provide opportunities for identity development and agency [190, 191]. *Hybrid spaces* blend features of typical STEM environments with aspects of students' home communities [192]. We have some reservations with aligning the 299B course with counterspaces (the course was positioned as complementary to the physics sequence) or hybrid spaces (the course was not hybridizing physics culture with a separate culture). There are some commonalities, for example challenging typical ways of being "good" at physics, and validating students' lived experiences and struggles. The relationship between the 299B experience and other physics spaces is worth teasing apart in future work.

5.9.2 Differences in what counts as "good" in each context

The normative identities within peer contexts differed from normative identities in the research context. Within the peer context, Cassandra described students' strengths as knowing how to solve problems or having some content knowledge. For example, she felt legitimized when she was able to solve a challenging math problem that even her professor couldn't solve. She also described an interaction with a peer where she brought her knowledge of integrals, and the peer brought his knowledge of quantum computing. "Good," in this context, referred to what people knew or were able to use to solve problems.

In contrast, what was celebrated in the research context was being able to be persistent and hardworking. Cassandra recounts her mentor saying "I really wanna work with somebody who's gonna stick with this and push and do something," suggesting that Cassandra interpreted persistence as being an important quality to doing research. Across the interviews with Cassandra, she never describes her mentor as valuing her specific content knowledge or skills. She also does not describe specific scientific skills or content knowledge as evidence of her worth as a researcher.

Cassandra, and likely other students, are experiencing different messaging about what it means to be good at physics between research and coursework experiences. Depending on a department's goals, we believe that this misalignment could inform changes at a departmental level. For example, if the department believes that coursework should align with the values of physics research, including valuing persistence through challenges, they might consider how the rewards structures of coursework could be shifted to value persistence in addition to conceptual and procedural knowledge. If a department believes that content and procedural knowledge are the end-goals of a physics undergraduate degree, research experiences could be adjusted to emphasize the development of conceptual learning. Or, a department could deliberately decide it values students gaining these qualities in different settings and allow for this misalignment to continue. That there is misalignment between normative identities in physics research and courses isn't necessarily bad; misalignment between what's valued in coursework and what's valued in research can be productive toward providing multiple pathways into physics.

However, misalignment between what is valued between research and coursework presents implications for equity. Prior research has described how what is recognized as "good" in STEM can look different across classrooms, which leads to students long-term identification (or attrition) within STEM disciplines [42, 71]. One could imagine how a student such as Cassandra could have enough peer experiences like the one in t_1 and leave the discipline before having the opportunities to see that she has other qualities that make her good at STEM. Depending on what faculty believe are important qualities to doing physics, we believe that we should aim to cultivate and recognize those in our physics coursework. Otherwise, the limited set of valued normative identities in physics risks losing students who have the potential to do well in physics research.

5.9.3 How might identities and relationships on one space afford different kinds of interactions in other spaces?

A rich area for future work would be to explore how shifts in identities and relationships within one physics space impacts students' identities and relationships in other spaces. This is aligned with prior research that has described how identity development in one setting can support identity development in other settings [74, 193]. Work by Fields shows that students' computer programming identities is built across multiple formal and informal settings [74]. Work by Sawtelle and Turpen describes a student whose affiliation with biology supported her development of a positive physics identity within an introductory physics for life sciences majors course [193].

While Cassandra describes different normative identities between physics research and peer settings, it is plausible that these can be connected. One can imagine how Cassandra's positive identity shift in her research experience could have fueled a positive identity shift with her peers, and vice versa. In other data (not explored in this paper), Cassandra credits the 299B course instructor with helping her understand that students bring unique approaches to solving problems. While Cassandra does not explicitly connect this to physics coursework, it's plausible that this supported her in seeing her peers in multifaceted ways. In a different vein, one could study how strategies for addressing misalignment between normative identities and personal identities could also move from one setting to another. For example, it's plausible that Cassandra's increased comfort seeking out interactions with her mentor could have influenced her becoming more outgoing in physics peer settings. Future work can study the various physics settings that undergraduate physics majors participate in and longitudinally observe students across settings to see how identity resources from one setting can support identities in others.

5.9.4 Equity implications for the design of research experiences

We believe these findings have several implications for the design of research experiences.

Cassandra's initial resistance to seeking out meetings at t_1 illustrates how it is not enough to simply tell students to knock on doors to find research experiences. We should also consider how these cultural expectations may sit in tension with students' personal histories. Courses such as 299B can lower the barrier to initiating research mentoring opportunities, and serve as valuable entry points for students to engage in research. This is especially important for students who might otherwise feel uncomfortable or unwelcome initiating first meetings with faculty.

Leaving the burden on students to initiate meetings may disproportionately favor more aggressive, or privileged students (e.g., students with more experience in higher education). Cassandra saw her mentor as being "hard to approach," and suggested that she might have been pushed away had it not been for the class. And while the process of "proving oneself" worked out well for Cassandra, we believe that mode of operation would likely feel threatening to other students. Given that many research experiences are acquired informally, and the kinds of expectations of research students are also implicit, leaving it up to students to initiate conversations could negatively impact many students.

The idea of "proving oneself" is highly gendered and racialized. "Proving oneself" evokes a sense of competitiveness to claim one's status, typically associated with male socialization. As Seymour and Hewitt describe, competition in undergraduate STEM is often seen by men as a challenge, but is far more threatening to women. They write, "in treating male and female students alike, faculty are, in effect, treating women in ways that are understood by the men, but not by the women." ([5] p. 261) How one proves themselves to Cassandra's mentor is also striking. One must be persistent and aggressive about scheduling meetings and demanding face-time. But this approach can feel unfamiliar to students who are less familiar with the "rules of the game," which can likely lead to inequitable learning opportunities. We recommend that research mentors reflect on the expectations and assumptions they have about working relationships and students, and how those might marginalize students.

5.9.5 Socialization into (problematic) meritocratic notions of physics research competence

By t_3, Cassandra buys into into the idea that physics students need to prove their worthiness or commitment to faculty in order to be worth their time. This perspective cues up the idea that physics is a meritocracy in which success is only limited by effort and ability, and that those who are unsuccessful simply did not try hard enough. Part of this stems from having seeing herself as having succeeded within this meritocracy. Cassandra interprets her prior struggle as having proven herself, and recasts other unsuccessful physics majors as simply too flakey to be worth faculty time. We offer an alternative interpretation: in becoming more like a physicist, Cassandra has also adopted problematic aspects of dominant physics culture.

We find the idea that science is a meritocracy problematic. Underlying the beliefs that students need to prove themselves and that failure is the fault of the individual is the assumption that the playing field is level. But myriad studies have shown that students from nondominant backgrounds have limited access to professional resources, opportunities for learning, opportunities for identity development, and recognition in STEM fields [5, 30, 37, 194]. Adopting competitive attitudes also comes at a greater cost for women, who have been socialized to be cooperative [5]. Even women who adopt competitive attitudes to succeed are often seen as unfeminine or have their successes questioned [5]. The idea that the playing field is level is simply not true.

Rather than seeing the purpose of university physics as sorting and filtering students, we offer an alternative vision for physics education that cultivates a diversity of successful trajectories. Within such a vision, we would see all students as having the potential to be successful at physics, and design for a diversity of pathways and starting points into the discipline. This involves questioning assumptions about why certain students are labeled as “flaky” or “lazy” [35, 186], reflecting on if it is possible that there are unstated expectations for how these students should engage with faculty [37], and understanding that these expectations may conflict with students’ cultural backgrounds. We also invite faculty to consider how those tensions could be mitigated. For example, for students who are hesitant to knock on doors it could be valuable to have lowered barrier-to-entry settings, such as undergraduate-focused seminars, where students talk with faculty about their research [195, 196]. It would also be important to support collaboration instead of competition, creating a culture of learning together (c.f. [197]) where we value individual’s growth instead of comparisons across students [148]. Explicit attention to the meritocratic notions of physics is essential to making physics more diverse and inclusive.

Chapter 6: Discussion

My dissertation studies the relationships and processes which shape students' participation within the discipline of physics. Studying this early disciplinary participation gives insight to how students are supported within or pushed out of physics, which is an important step toward cultivating a diverse set of physics students. This research occurs within two learning environments that I co-developed, a physics camp for high school girls and a seminar for early undergraduate physics majors to get started in physics research.

Using situated learning theory, I conceptualized physics learning to be intertwined with participation in physics practices and identity development. This drew my attention to relationships between students and the physics community. Specifically, I studied how students come to engage in the practices of the community and who they are within the physics community. Understanding how students become members of the physics community will provide valuable insights for fostering a diverse set of successful trajectories in physics.

In this chapter, I briefly summarize the findings from each chapter of the dissertation. I then synthesize across chapters to articulate my dissertation's contributions to the physics education research community and science education community. Next, I draw out several design principles for designers of physics learning environments, educators, and research mentors. I conclude this chapter by identifying several fruitful areas for future work.

6.1 Summary

Chapter 3 begins the work of deeply looking at the practice of *tinkering*, and illustrates what it looks like for students to engage in tinkering in the Summer Girls camp. I defined tinkering to be an approach to solving a problem or accomplishing a design task that uses ad-hoc trial and error. Tinkering contrasts with more abstracted, planned approaches to solving a problem, which we call *deliberate sensemaking*. This paper addressed the debate on whether or not tinkering was productive compared to deliberate sensemaking. Using fine-grained video analysis, I illustrated how tinkering can be productive toward some learning goals, but we should not consider it universally productive or unproductive. In one episode, tinkering led to more deliberate sensemaking. In the other episode, tinkering was productive toward engaging in some authentic design activities, but unproductive toward solving the design task at hand. I argue that instructors should reflect on why they value some kinds of activities over others, because a narrow view of what counts as productive can marginalize students. Not all students have access to the valued STEM practices within a discipline and some practices come more naturally to some some students than others. Having a narrow view of what counts as productive might mean that the valued practices are only accessible to a limited set of students. Broadening what counts as productive can make our classrooms more inclusive.

Chapters 4 and 5 take place in the context of a seminar for early undergraduate research experiences. Chapter 4 studies how students' engagement in scientific practices can be impacted by the joint work and interactions surrounding those practices. I characterized authentic scientific practices as scientific activities that are connected to one another and embedded within a scientific purpose. I characterized joint work along two grain sizes, the broader form and structure of the project, and the day-to-day patterns of interaction. Through three case studies, I illustrated how the forms of joint work impacted the degree to which students' engagement in scientific activities were connected and purposeful. For example, Frank had regular meetings with his mentor in which his mentor set daily objectives and they worked together on the same tasks. This supported Frank in having opportunities to seek connections between scientific activities and understand the purpose of his work. In contrast, Cassandra and her mentor worked asynchronously with sparse meetings, giving her limited opportunities to learn the broader connectedness and purposefulness. This research illustrates how it can be challenging for students to see the connectedness and purposefulness of their scientific activities without mentor support. Structuring opportunities for students and mentors to work collaboratively, or even just nearby, can support this understanding.

Chapter 5 is a longitudinal analysis of one case study, Cassandra, and her identity development within physics. This chapter studies how students' personal identities relate to the normative identities of the discipline. Drawing from Cobb et al. [42], I define normative identities to be the accepted and valued roles of physics students. This case study analyzes Cassandra's perceptions of normative identities that emerged in physics research settings with her research mentor and peer settings such as coursework and public student spaces. I illustrate how Cassandra's personal identity shifted in tandem with her perception of normative physics identities in ways that led to greater alignment between the two. This study revealed how scaffolded *entry points* that exist outside of traditional physics courses can support students' participation. These entry points can serve the role of initiating interactions (such as between Cassandra and her mentor) and giving students the opportunity to see members of the community as multifaceted people with a diversity of strengths and weaknesses.

Together these chapters give a broad picture of what it looks like for students to become physicists. In Chapter 3, I zoom in on what it looks like for students to engage in one disciplinary practice, tinkering. In Chapter 4, I consider how context and interactions between members of the community can foster authentic participation in practices. Finally, Chapter 5 considers how a student's physics identity develops within particular spaces and relationships over time. In the next section, I discuss implications of this work for the broader physics and science education communities.

6.2 Implications for research on physics learning

We should specify the ends toward which an activity is productive.

Often in physics education research, we argue that some kinds of student activities are "productive" without elaborating on the goals toward which the activity is productive. I argue that we should more explicitly state our learning goals when discussing interventions and evaluating student performance. Many kinds of goals exist in a physics classroom, for example: content learning, developing mechanistic reasoning [119], positive disciplinary affect [128, 129], expert-like epistemologies [46], and engagement in scientific practices [63–65]. These goals can often be in tension with one another.

In Chapter 3, I discuss how tinkering can be productive toward some teaching goals, such as supporting future deliberate sensemaking and engaging students in some valued design activities. Within this chapter, I illustrate how these goals can often be in tension, and instructors need to assess tradeoffs between these goals and the constraints of the classroom. The case of Neil in Chapter 4 illustrates a potential tradeoff between supporting purposefulness and having a tractable project. Neil's mentor developed a small project within the lab's bigger experiment, which led Neil to feel successful at his project and understand why his research helped the lab, but not the overall purpose of the lab's experiment. I argue that in evaluating student activity, it is important name the ends toward which an activity is productive.

Extending studies of communities of practice to physics research settings.

While communities of practice has been used as a framework to understand physics classrooms [198, 199], informal learning settings [162], teacher educator programs [200, 201], and undergraduate programs [62, 163], it has not been used to look specifically at the physics research community. Chapter 4 begins the work of analyzing what legitimate peripheral participation can look like in different physics research settings as students are apprenticed into the physics research community.

The physics research community is well-aligned with Lave and Wenger's description of a community of practice, and is a natural fit for the framework. They initially developed communities of practice to study apprenticeship into professions such as butchering and tailoring [59]. Similar to Lave and Wenger's studies of trade professions, the physics research community exists on a much longer timescale than a single course and has an ongoing history. Members of the community utilize a distributed repertoire of tools and resources to better understand physical phenomena. There is also a diversity of expertise, roles, and ways becoming part of the community.

Chapter 4 articulates different forms of legitimate peripheral participation in the physics research community, and how those bear on students' engagement in physics practices. The research projects took many forms, for example, designing a small device that is part of a larger project, a contained (but manageable) research project, and engaging students in a specific practice in great detail. All of these forms of legitimate peripheral participation exist as ways to bring people into the physics community, and afford different kinds of learning. In using a communities of practice lens, my work illustrates the diversity of forms of legitimate peripheral participation. This differs from other research on undergraduate research experiences, which aggregates across research experiences to look for common activities and learning outcomes [151, 156, 158]. Focusing on commonalities limits us to a narrow understanding of how one "typically" comes to engage in physics research—losing the ability to speak to important variations. Our field would also benefit from an understanding of the diversity of trajectories, and expanding our notions of how expertise is gained in physics. Understanding variations in how expertise is gained can help us be more responsive to individual students' needs and histories, and help us notice when physics learning is happening in non-normative ways.

Understanding shifts in identity requires looking at perceptions of the discipline.

Often in studies of identity development, researchers probe for disciplinary identities without also studying students' perceptions of the discipline. Chapter 5 illustrates how the extent to which students identify with physics can depend on their perceptions of who belongs in that discipline. In the case of Cassandra, the extent to which she identified with physics was not only dependent on shifts in her personal identity (e.g. becoming more outgoing) but also shifts in how she understood the normative identities of the discipline (e.g. coming to see physics peers in multifaceted ways).

This is important because identity research in physics education research often measures students identities in "physics" without considering how their views about physics might change. For example, the Persistence Research in Science Engineering project measures identity through the survey item, "Do you see yourself as a biology/chemistry/physics person?" [75, 202]. This survey, and similar instruments [203, 204] probe for students' physics identities without probing for students ideas about what the discipline is and the normative identities within it. Chapter 5 suggests that a favorable response to such a survey item could depend on changes in students' personal identities (coming to see themselves differently), their perceived normative identities (shifting views about what it means to be a "physics person"), or both. Without additional data, such as interview data, there are multiple plausible interpretations for a student response to that survey item. Andrew Elby and I make a similar argument in a paper that shows how students' self-efficacy, or confidence in research ability, can interact with shifts in students' views about the nature of science [205].

Moving our focus away from shifts in personal identities also presents some implications for instruction. Prior work has often suggested interventions that target students' personal identities, for example, by giving students verbal encouragement, cultivating interest through real-world examples, and having students do "values affirmation" exercises (where students identify things and people in their life that are important to them) [75, 204, 206, 207]. My research reveals that it can also be worthwhile to explicitly target normative identities and students' perceptions of normative identities. Restructuring our classrooms to allow for a diversity of normative identities may shift students' sense of belonging without putting the burden on students to shift their personal identities. For example, Cohen's *Complex Instruction* is a curriculum designed so that students bring a diverse set of strengths and backgrounds to a problem [208]. Had Cassandra's early physics courses been more like *Complex Instruction*, it's plausible that Cassandra would have found greater alignment between her personal identity and normative identities earlier. My research shines light on what alignment and misalignment between personal and normative identities looks like, and can support educators in noticing and addressing these misalignments.

Developing mechanistic models of access and exclusion in physics.

This work begins to chart the consequential features of students' access and exclusion in physics departments. In Chapter 5, I illustrate how perceived normative identities and their misalignment with personal identities can lead to exclusion and marginalization in physics. Aspects of these normative identities also emerged in other case studies or have been documented in the literature [5,8,181,194,209]. For example, Cassandra's initial perception that other people were "so smart" compared to her ties into the common belief that physics success stems from "brilliance" rather than "hard work." A study by Leslie [209] shows that this brilliance narrative is pervasive in physics, and correlates with gender and racial disparities. As another example, Cassandra's experience with the tutor who wanted her to solve a problem the hard way echoes the physics ritual of proving oneself through rigorous problems [181]. One could imagine an alternative normative identity in which it was valued to solve problems using the most simple, elegant solutions. While favoring simplicity is something that I personally have seen in physics, it was not present in Cassandra's accounts.

An important aspect of Cassandra's increased participation in physics was through non-traditional settings where she met other physics majors. In building relationships with peers, Cassandra bought into the brilliance narrative less, and came to see physics students as having a multifaceted set of skills and weaknesses. This ultimately led to increased participation in the community and greater sense of belonging. This chapter suggests that these non-traditional spaces may be important sites where normative identities become contested.

Interactions between students and mentors illustrate the ways that normative co-working patterns can support access or exclusion in physics. Cassandra described how it was common to knock on doors to ask for research, a norm that was also discussed by other students. This was discordant with Cassandra's personal identity, and she was excluded by this norm. Cassandra's mentor left the burden on Cassandra to initiate meetings and ask questions, whereas Neil's and Frank's mentors created regular opportunities for them to work together. This ultimately led to Neil and Frank having increased access to the physics research community, whereas Cassandra's access was more limited.

In the next section, I describe how these insights can bear on classroom design and teaching practice.

6.3 Design principles for physics learning

In this section, I describe several design principles for physics learning environments, including classrooms and research experiences. Design principles are underlying claims about learning that guide the design of future learning environments [13, 210]. These principles are not intended to be prescriptive rules for teaching, but rather, to highlight more generalizable strategies toward supporting some learning goals.

Instructors should articulate and reflect on their teaching goals in trying to evaluate if their teaching is working.

I see this principle applying to a broad set of teaching settings. In Chapter 3, I argued that the productivity of student activity depends on one's goals. To promote better alignment between teaching goals and learning outcomes, it is productive to articulate and reflect on one's goals. This can help instructors become more aware of tensions as they arise in the moment, and be more reflective about judgments that they make. These reflections can become especially worthwhile when designing for equity; as Chapter 3 discusses, it is possible to exclude students by only narrowly valuing some design practices as "productive."

Some avenues toward more reflective teaching practice include creating space for reflection after instruction, and pausing to reflect before intervening. While working on a pedagogy course for engineering peer educators, my co-designers and I wrote down our goals early on, had weekly discussions and journaling of our teaching, and used our teaching goals to develop assessment rubrics. Having explicit negotiation of our goals and recording them in written form supported our reflections on the course. I elaborated on this process in a conference paper about the design of the course [211].

In Chapter 4, interviews with research mentors suggested that mentors deliberately made instructional decisions based on their goals. For example, Neil's mentor valued students being able to see the "arc of a smaller project," because it created opportunities for students to feel proud of their work. Frank's mentor wanted students to see a project "from the ground up" (i.e., involving students in the formulation of research questions from background knowledge) because he thought that would be a more authentic experience. I believe that research mentors would benefit from having structured opportunities for reflection and conversation with others to discuss and refine their mentoring goals. One model for this is the networked mentorship strategy implemented by the National Astronomy Consortium (NAC) [212], where several mentors form a collaborative network of support for each student. Such a model can likely support mentors with regular opportunities to reflect on their teaching goals.

The connectedness and purposefulness of scientific activity needs to be scaffolded by old-timers in the scientific community.

Chapter 4 demonstrates how it can be challenging for students in research experiences to glean the connectedness and purposefulness of their work. I believe, however, that connectedness and purposefulness are essential to an authentic physics research experience, and are a worthy focus when designing undergraduate research experiences. The three case studies illustrate that students do not just come to an understanding of these features on their own, but need mentors' help in understanding the broader importance of their scientific work. In the design of learning environments, old-timers should explicitly support these meta-level discussions, rather than focusing on individual skills. For example, students may be able to learn to code on their own, but they need a mentor's help in understanding how coding can be useful within a given project.

Opportunities for spontaneous and frequent joint attention promotes access to scientific practices and relationship building.

Chapter 4 illustrates how what students learn depends on the forms of joint work between students and mentors. Both Frank and Neil had many interactions with their mentors that involved co-working with joint attention maintained. Frank's research activities occurred in regularly scheduled meetings that were supervised by his mentor. Neil and his mentor often worked on different tasks, but nearby, so that Neil could ask questions and his mentor could check in on him as he was working. On the other hand, Cassandra's collaboration with her mentor (in Chapter 4) was done asynchronously with fewer meetings. This led to Cassandra having many unanswered questions about the connectedness and purposefulness of her work. I argue that if mentors value responding to students' questions and supporting this kind of learning, they should go beyond responding to questions when asked. It is also important to provide opportunities for questions to spontaneously emerge that are embedded within the work environment. For example, mentors could periodically work in the same space as mentees (even on a different task) so mentees can easily ask questions.

Early entry points that support faculty-student interactions increase access to the physics research community.

In Chapter 5, I discussed how Cassandra initially was hesitant to reach out to faculty on her own, even though it was the departmental norm to do so. This work illustrates the value of creating well-supported environments for students to interact with members of the physics community early on. Often in physics departments, students get research opportunities through informal interactions and word-of-mouth, but this risks losing students who are less networked, and less familiar with university culture (e.g. first-generation college students). Multiple interviewees, including Frank, expressed having trouble getting faculty to respond to his requests for research experiences prior to 299B. Other students, including Cassandra, expressed discomfort in initiating conversations with faculty. Courses such as 299B can lower the barrier to these conversations and make research experiences more accessible.

Entry points that support regular interactions with peers can facilitate more nuanced understandings of the physics community.

In Chapter 5, I also identified how tutoring and the S-STEM scholarship program were entry points that supported Cassandra in meeting other physics majors. These entry points were opportunities for Cassandra to build deeper interpersonal connections, and helped her see physics majors in multifaceted ways. This ultimately impacted the way that she saw herself within the community, and how she engaged with others around physics content. Creating and supporting these environments where physics students develop strong communities contributes to more multifaceted understandings of peers, and can likely support students in staying in in the major [165].

6.4 Areas for future work

In this section, I outline several rich areas for future research. These threads are based on findings from the dissertation as well as questions that emerged in preliminary analyses of other data in the data set.

What are the ways in which students manage identities in the moment?

One area for future work is to study in greater detail how students manage aspects of their identities in physics spaces. In collaboration with Chandra Turpen, we frame this question as, what are students expected to "check at the door" when they come into physics? Several students in the study also shared aspects of their lives that they didn't feel comfortable sharing to faculty and classmates in physics spaces (e.g., personal turmoil, mental health concerns). Some students also found ways to explicitly resist and position themselves apart from normative identities. For example, Cassandra publicly declared her other-ness in physics spaces by announcing loudly that she was an "old lady."

Future work would analyze these salient descriptions of identity work across several students and consider how the "physics major norm" differentially impacts students from diverse backgrounds. Additionally it would study what aspects of identities are welcome or not welcome across multiple physics settings. One might expect that discussions about a student's racialized or gendered physics experiences would be more welcome in a setting such as S-STEM rather than a traditional lab class. Understanding how individual physics spaces require more or less identity work for students with diverse backgrounds would be an important step toward fostering more inclusive physics departments.

How do physics identities and practices move across settings?

Students experience physics in many kinds of settings, all of which afford different resources for identity development and engagement in practices. An important area of study is to understand what these different settings afford for students' long-term participation in physics as they move into new settings.

Within the two studies in this dissertation, each setting has a different relationship to the physics disciplinary community; within the physics research seminar, students engage in authentic research with physics experts, whereas students in the camp primarily work with other students on student-led projects. Next steps would be to look across these two setting to understand how proximity to the center of the physics community affords access to different kinds of participation in physics. Future work could even study the same student moving from one setting to the other, as multiple former students from the Summer Girls camp have also taken Physics 299B.

Understanding how aspects of students' identities and engagement in practices can translate into other settings is an understudied area of research. There is a large body of work illustrating that skills and identities do not translate across settings. For example, several studies have shown that adults and children can perform complex mathematics in non-classroom settings, but are unable to do more "school-like" math problems [213–215]. While the purposes of these studies have, in part, been to show that context matters for how people solve problems, they do suggest that practices and skills do not transfer easily. Other work has shown that identities are developed across settings, instead of just within a single setting. For example, a dissertation by Fields [74] looks at how childrens' identities as learners of Scratch (a computer programming language) developed across several settings: a classroom, an after school club, and online message boards. My work would consider how students experience "physics" across an even broader set of settings—classrooms, research experiences, student groups—where the activities themselves look very different.

Cassandra's case study points to several starting points for this work. Researchers could observe students in various physics spaces (research contexts, 299B, S-STEM, SPS) to understand what kinds of practices and identities are present in each. Longitudinal analysis of individual students would shed light on how identities and practices move from one setting to another. For example, could the development of a strong physics identity in a research setting support students as seeing themselves and being recognized as a physicist in other settings? Would practices that students engage in while doing physics research (e.g. informal order of magnitude calculations) also be brought into a physics course? This study would contribute to a deeper understanding of the dynamics of physics identity development.

How can we deliberately bridge research and practice?

In future work, I would like to also more deliberately bridge research and practice, using tools from Design-Based Research [210]. Design-Based Research involves the iterative creation of complex educational environments, and conducting research to understand how those environments function. In my dissertation work, I have developed courses rooted in research-based strategies, and conducted research on those courses. For example, I recently co-authored a paper on the design of a pedagogy course for undergraduate peer educators in engineering courses [211]. This paper described how we deliberately designed toward several teaching goals and evaluated the extent to which our activities met those goals. In future work, I would be excited to iterate on classroom design and see how the research can directly support better classroom practice.

How can we design for proudness and student ownership?

One common thread across interviews with Summer Girls and 299B students was a strong sense of ownership over their projects. This ownership also reflects what Little [169] describes as proudness, the sense of accomplishment and being proud of one's work that follows a period of frustration. Within learning settings, I would like to think about how we design for proudness rather than demonstrations of learning.

While students in both Summer Girls and 299B expressed feeling proud of their work, I suspect that these are for different kinds of reasons. In Summer Girls, students designed their own projects and often incorporated their personal interests into them. Students' approaches were unique and tended to be personally meaningful. In contrast, 299B students had virtually no say in the design and form of their project. One commonality across settings that may have supported proudness was that the settings disrupted the tendency for students to make direct comparisons between themselves and others. Work by Secules [35] has shown that having public opportunities for direct comparisons (e.g. seeing who can finish a task first) can often lead to classroom hierarchies and marginalization of students. In both Summer Girls and 299B, students' projects were unique enough that it was not easy for students to make direct comparisons. Analyzing across the two settings would be fruitful to study how proudness emerges, and could provide interesting contrasting cases.

What does it look like for a community of practice to become transformed?

Throughout this dissertation, I have treated the physics community of practice as unchanging. My research has asked what it looks like to bring people into the community, and treated the community has having a relatively fixed (though diverse) set of beliefs and practices. To some extent, it is fair to model the community this way; the timescale at which disciplines change is tends to be longer than the scope of this study, and such change is hard to understand using a few case studies. But as a member of the physics community myself, I am dissatisfied with holding the physics community as a constant because there are many aspects of the community which I care to change. This dissatisfaction with our normal ways of doing things has significantly impacted my classroom design and my choice of research themes.

The moral challenge of holding the physics community as constant is especially evident at the end of Chapter 5. Cassandra buys into the belief that physics is a meritocracy where faculty separate the weak from the committed. This illustrates how the problematic, exclusionary aspects of our culture become reproduced through through bringing people into our community.

Instead, I would like us to think more deeply about how our own physics community changes over time. Such an understanding would support us in implementing sustainable change. As a suggestion for how to make this research question more tractable, one could study how change efforts happen in departments and how it is possible to measure such change. For example, within the physical sciences at the University of Maryland, graduate programs are implementing (or considering implementing) changes to graduate admissions selection criteria. These changes would select for holistic skills, rather than exam scores and grades, to better align with what faculty value in graduate students. It would be interesting to study how these change efforts can be catalysts for (or perhaps even a result of) changes in faculty attitudes toward graduate education.

Even though Lave and Wenger describe communities as changing through members' participation [59], understanding what the changes in a community of practice look like is understudied. Most communities of practice work in physics education research tends to hold the community constant. Engestrom's construct of *expansive learning* may be a useful approach to looking at how communities change [16]. Expansive learning looks specifically at the transformation of culture. As Engestrom asks, "Is learning primarily a process that transmits and preserves culture or a process that transforms and creates culture?" While situated approaches often consider learning "as one-way movement from incompetence to competence" [16] expansive learning foregrounds how these measures of competence change over time. Looking at transformation as the focus for analysis changes can likely illuminate mechanisms by which communities change. This understanding would support the deliberate development of more effective change efforts, and how we might bring students into the community as agents for change.

Appendix A: Transcript Notations

1. ( ) Italicized Text within parenthesis refers to facial expressions, gestures, body posture, participant actions, etc as noticed by the transcriber in the video data
2. : Colon indicates a prolonged syllable with the number of colons indicating roughly the duration of prolongation
3. > < This use of brackets indicates that the bracketed text is uttered faster than the surrounding speech
4. Underlining: Syllables that are stressed are underlined.
5. Capitalization: Capitalization is used not for grammar but to indicate stress in the speech.
6. Punctuation is also used to indicate intonation rather than for grammatical purpose. So a period at the end of a word would indicate an intonation signaling the end of a sentence or utterance. Not all utterances end with a period intonation.
7. (.) Parenthesis with a period is used to mark a short untimed pause
8. (2.5) Parenthesis with a number inside are used to mark a timed pause, with the number representing the number of seconds (resolution of a tenth of a second) of silence.
9. \...\ utterances written within two backslashes indicate overlapping speech
10. – short dash indicates cut-off of speech

Appendix B: Interview Protocols

B.1 Summer Girls Interview Protocols

B.1.1 Pre-Interview

- Why were you interested in participating in summer girls?

- What is it about physics that interests you?
  Were there certain people or experiences that helped you get involved in science?

- What other experiences have you had, related to physics or science? What were those like?

- What college majors or careers interest you? Why?

- How would you describe yourself as a student? Walk through a day in school. What is that like? What do you think of your science and math classes in high school?
  Do you have a favorite? Least favorite? Why?

- Describe some situations in which youve worked with other students in your high school?
  What was that experience like for you? Do you find it helpful to your learning? (Ask questions about classmates and friends, to find out what kinds of students take science, etc)

- Can you think of a time when youve learned something completely new? What was that? What was that like for you?

- Have you had any experiences programming?
  If so: Describe those experiences. What were those like? Do you know other people who have had experiences programming? What are they like? Do you hang out with them? (trying to get at relationships)
  If not: Do you know other people who have had experiences programming? What are they like? Do you hang out with them? (trying to get at relationships) Is programming something you have considered doing?

- What types of skills do you think are important to be a good science student?
  How do you think the skills that are needed to be a good science student in

school relate to skills that are needed to be a good scientist?
Do you have any of these skills now?
Do you think you are good at science? How do you know?

- What words describe you AND your interests?
  Which aspects are most important for someone to know about you? Why?

B.1.2 Mid-Interview

- How has the camp been so far?

- What activities have been most interesting? Least interesting?
  What about ___ has been interesting?

- What has the Arduino component been like for you?

- Can you describe to me what your group is like on the Arduino project? What is your role in your group like?

- Youve been working in new pairs each day. Have you noticed any differences in how you work with different people?
  How does it compare to other experiences working in groups?
  In which pairing/groups do you feel like youre learning more? Why?

- Are there skills you feel like you bring to your group?

- Do you feel like youre learning anything during the Arduino projects? What?

- What parts have been most interesting? Why?

- While working with the Arduino, did you ever encounter something that was particularly challenging or frustrating?
  Why was it frustrating? What happened?

- How was your experience working in groups in the Arduino project?

- Can you tell me about your final project?
  How did you come up with that? (What alternative ideas did your group come up with? how did you decide on this one?)
  Can you describe what you have thought on the project implementation so far?
  What difficulties do you anticipate in doing the project?

- Can you think of a time in Summer Girls when another student seemed to know more than you did about a topic?
  Can you talk about that experience?

B.1.3 Post-Interview

- How did the camp go for you?
  What about it was ___ for you?
  Are there specific instances that stick out to you as being ___?

- What aspects did you most enjoy?
  Why was that enjoyable for you?

- What aspects did you enjoy the least?
  Why was that ___ for you?

- What was most challenging for you?
  Can you think of a time in ___ that was particularly challenging for you? What happened?

- How was the Arduino project for you?
  Within Arduino, how was coding? How was building and circuitry?

- How did your final project go?
  If their project changed significantly: When/How did you decide to change your project?

- What was it like working with your partner/group on the Arduino project?

- Could you see yourself doing something like the Arduino stuff in the future?

- If one of your friends was thinking about taking Summer Girls, how would you help her decide if she should attend?

- If one of your friends was coming to Summer Girls, what would you say to her to help her get the most out of her experience?

B.2 299B Interview Protocols

B.2.1 Pre-Interview

- Do you know what you want to major in? Why? When did you decide this?

- What is it about physics that interests you?
  Were there certain people or experiences that helped you get involved in science?

- Describe some situations in which youve worked with other students in your high school?
  What was that experience like for you? Do you find it helpful to your learning?

- Can you think of a time when youve learned something completely new?
  What was that? What was that like for you?

- Why did you decide to take 299B
- What do you think doing research will be like?
- What about doing research most interests you?
  Is there anything youre excited for?
  Is there anything youre nervous about?
- Before taking the class, have you thought about pursuing research experiences on your own?
  What was that like?
- What types of skills do you think are important to be a good physics student?
  How do you think the skills that are needed to be a good science student in school relate to skills that are needed to be a good research intern?
- How do you think the skills that are needed to be a good science student in school relate to skills that are needed to be a good physicist?
- Do you have any of these skills now?
  Do you think you are good at science? How do you know?

B.2.2 Post-Interview

- Are you still majoring in ___?
- What are you considering post-graduation?
- Can you tell me about your research in 299B?
  What was that like?
  Why did you decide to take 299B?
- Was there anything that surprised you about doing research?
- Is there anything from the project that youre particularly proud of?
- Did you ever encounter something that really challenged you in your research?
  What did you do when you encountered that?
- Did you learn anything about the research process this semester?
- What did you think research would be like before you started?
- Were there any aspects of your physics classes that were relevant in your research?
- What else could have been taught to prepare you for research?
- How confident do you feel that youd be able to do another research project?

- How did the 299B class go? Do you think your research experience would have been different without the class?
- What skills or tools do physics students need to be successful researchers?
- Did you feel or not feel a sense of community in 299b?
  What contributed to that?
  Do you feel a sense of community in the physics department?
- Did you ever interact with other 299B students outside of class?
- Would you add anything to the course to prepare students for their research projects better?
- If one of your friends was thinking about taking this class how would you help them decide?
- If you knew one of your friends was going to take it, what would you say to them to make the most out of their experience?
- If you could go back and change anything, such as picking a different project, what would you change?
- Do you have interest in pursuing research in the future?
- Do you consider yourself good at physics? How do you know?
- Why do you think there is so little diversity in physics?
  Do you think that has impacted your experience here?
- Is there anything else about you that bears on your experience as a student here?

B.2.3 1-Year Follow Up

- Are you still majoring in ___?
- What are you considering post-graduation?
- Are you still doing research now?
- Can you reflect on your research in 299B?
  What was that like?
  Was there anything you feel like you gained from that experience?
- What aspects do you recall as most enjoyable?
- What aspects do you recall as being frustrating or least enjoyable?
- What was most challenging for you?

- Is there anything you feel like youve learned about the research process?
  What did you think research would be like before you started?
- What was your relationship with your research mentor(s) like?
  Was there any aspect of this relationship that was particularly important?
- How confident do you feel about your ability to do research now?
  Were there any experiences that contributed to your confidence or lack of confidence?
- Can you reflect on the 299B class?
  Do you think your research experience would have been different without the class?
- Looking back, is there anything you would add or change in the course to prepare students for their research projects better?
- If one of your friends was thinking about taking this class how would you help them decide?
- If you could go back and do something differently what would you change?
- Do you have interest in pursuing research in the future?
- Do you consider yourself good at physics? How do you know?
- How much would you say you feel like a physicist?
  Were there any particular experiences that contributed to that?
  Are there any other experiences like that which contributed to that sense?
  How much would you say your research, coursework, outreach, teaching contributes to that?
- Do you think that your race or gender identity contributes to your experience in physics?
  Are there any other aspects of your identity that you think contribute to your experience?
- Why do you think there is so little diversity in physics?
  Do you think that has impacted your experience here?
- Is there anything else about you that bears on your experience as a student here?

Appendix C: Summer Girls Data Collection

2014					
Group #	Members	Pre-Int	Mid-Int	Post-Int	Classroom Video
1	Coral Bianca	x x	x x	x x	x
2	Sienna Indigo	x	x	x	x
3	Ruby Amber Violet	x	x		x
4	Poppy Pearl Ivy	x	x		x

Table C.1: Data Collection for 2014 Summer Girls

Group #	Members	Mid-Int	Classroom Video
1	Hazel Olive	x	x
2	Rose Scarlet	x	

Table C.2: Data Collection for 2013 Summer Girls

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