UNDERSTANDING STUDENT EXPERIENCES IN INFORMAL PHYSICS PROGRAMS USING THE COMMUNITIES OF PRACTICE FRAMEWORK

By

Brean Elizabeth Prefontaine

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ABSTRACT

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Studies on physics identity have shown that it is one of the main factors that can predict a person's persistence in the field; therefore, studying physics identity is critical to increase diversity within the field of physics and to understand what changes can allow more women and people of color to identify with the field. Informal physics spaces are not only made up of youth participants, but also facilitators who can be undergraduate or graduate student volunteers. In this work, the experiences of facilitators within informal physics programs are investigated as spaces for physics identity development. Thus, the driving question for all of this work is: In what ways can participating as a facilitator within an informal physics program affect identity development? The data for these studies were collected through observations, written artifacts, and semi-structured interviews with those who facilitated the informal physics programs. In order to understand more about the experiences of the facilitators, the informal physics programs were viewed as Communities of Practice (CoP), and the CoP framework was operationalized within the context of these spaces. First, stories from two physics graduate students out of the interview sample are presented to provide a context for testing the feasibility of the extended framework and to identify how experiences within an informal physics program can shape physics identity development. Then, the operationalized CoP framework is used to study three distinct informal physics programs to understand the structures that support physics identity development. Finally, informal programs that combine physics and music/art are examined with the operationalized CoP framework to understand how these blended spaces can form communities of practice and support identity development. Analysis showed that the CoP framework is an effective tool for analyzing informal physics programs and highlights the structures that lead to identity development. These findings indicate that informal physics programs that operate with a CoP structure can provide valuable experiences to undergraduate and graduate facilitators that lead to physics identity growth.

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CHAPTER 1: INTRODUCTION

The physics field has been grappling with issues of diversity, equity, and inclusion for some time. Statistically, women and people of color are significantly underrepresented in the field compared to US and college populations [1-2]. Members of these groups are significantly more likely to encounter external environmental conditions of harassment, bias, and hostile climates [3-8] along with internal struggles of stereotype threat, imposter syndrome, a lack of a sense of belonging, and a fixed mindset [9-12]. Often these external and internal challenges can be intertwined and feed off of each other to create a difficult situation for women and people of color. Some initiatives have been put in place to address these issues. In particular, physics organizations around the world such as the American Association of Physics Teachers (AAPT), the American Physical Society (APS), and the Institute of Physics Ireland (IOP) have been developing strategies to recruit and retain more women and members of underrepresented groups. Some examples include the APS Bridge Program focused on addressing both internal and external challenges, women in physics conference series (ICWIP, CUWiP) focused on both internal and external challenges, and organizations such as APS and AAPT adopting codes of conduct at professional meetings focused on mitigating external environments [13-14]. Locally, however, physics departments must make efforts to support students, staff, and faculty who may be marginalized and oppressed [15-16]. Oftentimes students do not know about or have access to regional, national, or international initiatives whereas efforts made by their physics department can be more visible and easily accessed. Additionally, students often have a chance to form relationships with others in their physics department and so there is a sense of familiarity with those who are delivering the interventions. Overall, a systemic lack of support for physics undergraduate and graduate students' development of identity and sense of belonging in physics negatively impacts their career path, particularly for those from underrepresented groups in physics [4-6,9,12, 17-19].

Identity, and more specifically a person's self-association with physics, has been identified as a leading factor in predicting a person's future career path involving physics [20-22]. Factors such as student attitude, self-efficacy, agency, a sense of belonging, and motivation are understood to be important for building identity and addressing the number and diversity of students who persist in STEM subjects [9,24-26]. However, for students of color, women, and other marginalized groups coming into the field, building a physics identity necessarily intersects with their other identities and experiences [3, 17-18, 23]. In some cases, these intersecting identities may not align with current cultural norms and perceptions established by some members of the field surrounding who should be a physicist [18, 27-28]. For example, a study conducted by Hyater-Adams et al. used the Critical Physics Identity framework (CPI) to look at how experiences and structures impact the formation of Black physicists' identities. They found that both internal thoughts around who can be a physicist and external ideals put forth by the community and others external to the community about who can engage in physics discouraged participation in physics and therefore negatively impacted physics identity [18,23]. Since the internal and external recognition of "having the ability to be a physicist" has one of the biggest impacts on physics identity development, it is clear that the current climate of physics allows members of marginalized groups to struggle to participate and persist in physics, preventing changes in the landscape of the field. Without the consideration of intersecting identities, the national, regional, and local efforts described above will not be successful in supporting the members of physics who experience marginalization and oppression.

In order to understand how a physics identity develops, we must first understand what activities a person partakes in that fosters this development. To understand a student's experience with physics, we need to look at their interactions with not only the content but also the wider physics communities in which those people and activities are embedded. A student will take courses in physics and interact with members of a physics community, such as other physics students and professors in their class. There can be many communities within physics such as research communities within specific areas, online learning communities of physics professors, or learning assistant communities. Some may argue that physics as a whole is a community with students, professors, and researchers all working toward understanding more about the universe. Whether we look at physics as one large community or at the smaller physics communities, we can still see how a student in a physics classroom might interact with other members of a physics community.

However, a student may also interact with physics outside of a formal classroom setting in which they are attempting to expand their physics knowledge - however, they experience these out of classroom interactions as either a learner, consumer, or as an educator. For example, they may discuss physics concepts with their family and friends, read popular physics books, or listen to a physics podcast. On the other hand, they may participate in an organized effort, usually in an informal setting, that is focused on teaching physics to others. In this study, we are particularly interested in these organized informal physics programs and how those experiences impact the undergraduate and graduate physics student who participates as either a volunteer facilitator or as an audience member. In the following section, I describe informal science learning, give a brief history of the study of informal science learning, and describe how the study of informal learning can be situated within discipline-based education research, specifically physics education research.

1.1 Informal science learning

Outside of school, there are many opportunities to learn science. The learning that takes place outside of formal educational settings is often referred to as informal learning. Informal learning (sometimes referred to as free-choice learning, out of school time, and nonformal) is characterized by learner agency and is often learner-centered. Participants can opt in or out of the experiences, and they often have a say in the content and how they can engage with the content. The Committee on Learning Science in Informal Environments was established to produce a consensus report (published in 2009) that would characterize the many different ways that informal science learning takes place. Throughout their work, they proposed the "strands of science learning" framework that helps frame what is meant by informal environments. These six strands are included below [29]:

- Strand 1: Experience excitement, interest, and motivation to learn about phenomena in the natural and physical world
- Strand 2: Come to generate, understand, remember, and use concepts, explanations, arguments, models, and facts related to science.
- Strand 3: Manipulate, test, explore, predict, question, observe, and make sense of the natural physical world.
- Stand 4: Reflection on science as a way of knowing; on processes, concepts, and institutions of science; and on their own process of learning about phenomena.
- Strand 5: Participate in scientific activities and learning practices with others, using scientific language and tools.
- Strand 6: Think about themselves as science learners and develop an identity as someone who knows about, uses, and sometimes contributes to science.

It is helpful to consider these six strands when trying to define what "counts" as informal science learning. For instance, learners may go visit a planetarium and learn more about the solar system and then go home and talk to their parents about planets. Both of these instances are the learner engaging with science learning outside of the classroom, and so both of these instances can be considered informal science learning even though they take place in different settings. For the purpose of this dissertation, we are considering informal science learning that takes place within a structured program or "designed settings" [29]. These designed settings, which can be thought of as museums, afterschool programs, science centers, etc., are still learner-led but also contain some structure for design elements that were planned by facilitators. These programs can be funded through universities and allow for set times when the learners and facilitators engage with science topics outside of the confines of a traditional classroom (i.e. they are able to explore topics that are of interest to them and there are no grades attached to the activities).

1.2 Discipline-based education research and physics education research

The 2012 report from the National Academies titled Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering details, among other things, the history of discipline based education research (DBER) and the different fields [30]. Below I have briefly summarized the history of DBER and physics education research (PER) to provide some historical context to where my work is situated.

DBER is education research that is "grounded in the science and engineering disciplines and addresses questions of teaching and learning within those disciplines" [30]. This type of research can be traced back to the early 1900s but came more into focus in the 1980s and 1990s. However, in the 1950s and 1960s, the launch of Sputnik created a realization that the United States needed more scientists and engineers to be competitive with the rest of the world. In response, the

National Science Foundation funded science curriculum development projects that included scientists along with academics. True DBER work came around during the period between 1970 and 2000 as it started to gain recognition within the individual fields of study.

PER is a form of DBER in which education research takes place within the context of physics as a discipline. There were concerns about physics education as early as the late 1800s which led to the formation of the American Association of Physics Teachers (AAPT) in the 1930s [31]. The national concern about being scientifically competitive as a result of the launch of Sputnik led to physicists being involved with efforts to improve science education. All levels of curriculum were revised during this time period with large-scale undergraduate physics curriculum specifically targeted at the University of California, Berkeley, the California Institute of Technology, and the Massachusetts Institute of Technology. However, the first groups doing work that could be called PER were at the University of California, Berkeley and the University of Washington. The first PhD students to graduate in PER were in the late 1970s. Discipline societies started recognizing PER with the American Physics Society adding an education officer in 1986 and issuing a policy statement recognizing PER as a research area within physics departments in 1999. Recent advances for the field include an annual PER conference and proceedings as well as an established journal in the prestigious Physical Review line, with researchers at over 50 different colleges and universities [32]. To this day, PER is still a growing field with the need for more postdoc positions and faculty hired with PER backgrounds.

1.3 Informal physics settings

PER has been concerned in the past decade with understanding the identities of physics students. The findings of these identity studies have been used to suggest ways to leverage formal classroom learning to increase belonging and potentially create a more inclusive physics culture

[33]. Focusing on formal environments makes sense from an instructor perspective; however, what has been largely overlooked are the informal experiences where undergraduate and graduate students freely choose to interact with physics outside of their coursework.

Informal learning is differentiated from formal learning by students' degree of agency and voluntary participation, making them potentially very powerful experiences for identity [29]. Informal learning at the college level is often found in opportunities that are funded and offered through the physics departments, which allows students to interact with physics content and practices through public outreach. One such example of this is the American Physical Society's officially sanctioned student organizations, Society of Physics Students and Sigma Pi Sigma, which list "outreach services to the campus and local communities" in their mission statement [34].

Informal physics learning can take place in a variety of settings and can include events or activities that physicists might call "outreach" or "public engagement." Many common physics outreach programs involve two groups of participants: "audiences" or members of various publics and "facilitators" who are usually physicists and physics students.

1.4 Investigating facilitators and not participants

While a large body of research in the adjacent field of science education is focused on the impact that participation has on the youth and public audiences in informal learning environments, in most of this work we look at how volunteering to facilitate these programs impacts the identity of facilitators, with a primary focus on undergraduate and graduate physics students. We hypothesize that the environments promoted by informal learning programs allow facilitators to explore the intersection of their different identities, including their physics identity. A form of understanding and supporting intersectional identity development is through membership in

Communities of Practice (CoPs) [35-38]. Briefly, the Communities of Practice framework was theorized and developed in 1991 by cognitive anthropologists Jean Lave and Etienne Wenger. Since then, this framework has been used in a variety of fields, including education research, to better understand how groups of people interact with each other and how identities are developed within the context of those groups. More detailed information about the CoP framework, the construct of identity, and how the two are related is included in Chapter 2.

1.5 Scope of Dissertation and Research Questions

This dissertation is a collection of work that focuses on how informal physics programs can facilitate physics identity development among both facilitators and participants. The first portion of my work focuses on the use of the Communities of Practice framework to understand how facilitators within informal physics spaces develop a physics identity within the community. First, the framework was explicitly operationalized to be used in the context of informal physics programs. Chapter 4 of the dissertation involves a thorough discussion about all of the elements of the framework and the operationalization process with data from one informal physics program. Then, the operationalized framework is applied to three different informal physics programs so that we can better understand the experiences of the facilitators and the structures within those programs that facilitate physics identity growth (Chapter 5).

These first few studies all focus on the experiences of facilitators within informal physics programs that focus on physics concepts. It is evident from our own work and other's work that these experiences are important. However, I personally became interested in how informal physics spaces that bring in other interests (such as sports or art) could support diversity and inclusion within physics. For this reason, this dissertation then discusses work that focuses on programs combining physics and art and how those programs support both physics identity development and other identity development among participants (Chapter 6).

This collection of work addresses the fundamental idea of identity development within informal physics spaces. My goal in this dissertation is to use the Communities of Practice framework to understand the nuances of these experiences within informal physics spaces and how they can lead to physics identity development.

Within this focus, there are many research questions with a smaller scope that guide the work. These questions include:

- Can an informal physics program function as a community of practice?
- Can we operationalize the Communities of Practice framework to help us establish membership (and therefore identity) within the community of practice?
- What structures and/or mechanisms within an informal physics community foster (or hinder) membership and identity development?
- To what extent did a community of practice form within a new physics and art informal program?

In Chapter 2, I will provide an overview of the theories (identity and Communities of Practice) that have provided a framework to the studies. In Chapter 3, I give a brief description of the methodology and approach that I took for this work. In Chapter 4, findings from our operationalization of the Communities of Practice framework for informal physics programs are discussed and examples of how the framework is useful for understanding these spaces are presented. In Chapter 5, the operationalized framework is applied to three informal physics programs so that we could gain a deeper understanding of the structures that provide support for identity development among the facilitators. Chapter 6 is where the work evolves to consider informal physics programs that focus on the relationship between physics and the arts (such as graphic design) and how those spaces can allow for supporting diversity among those who form a physics identity. Finally, a conclusion which provides an overview of all of the work is presented in Chapter 7.

CHAPTER 2: THEORETICAL BACKGROUND

Within this chapter, I provide an overview of identity and a brief history of the Communities of Practice framework, including a discussion of other fields where it has been utilized. The three crucial characteristics that define a community of practice as well as other constructs within the framework are explained in detail. I also discuss how the framework has been used within the physics education research community and end with a discussion about why this framework is a viable choice within the context of this study.

2.1 Identity

A broad definition of identity refers to the qualities and attributes that make a person (or group) who they are and is often aligned with sociocultural labels, such as gender, race, and socioeconomic status, that allow for categorization of individuals and groups [39-43]. More specifically, identity has been established as a social construct that links the individual with the social world by translating social norms to self-categories and establishing positionality of individuals and their relationship with other members of society [42-44]. In 1979, a psychologist named Henri Tajfel proposed social identity theory which said that groups which people belong to are important because they are sources of pride and self-esteem. In other words, groups can give us a sense of belonging to the social world or provide us with a sense of social identity. Examples of these groups might include our family, a church group, a sports team, or a social class [45]. Therefore, our understanding of self and identity is dynamic, constantly subjected to change, and reassessed and molded by interactions of our individual world with social relations and collective spaces [35].

Furthermore, research has determined that the individual idea of self is formed by a series of identities that interact with each other, i.e. an individual contains multiple parts and each part has something to contribute [18-19, 46]. For example, a person can simultaneously be a physicist, a Black woman, a runner, and a mother; all of those identities overlap and depend on each other to make the individual whole. The idea of many aspects of identity influencing how one interacts with the world is also referred to as intersectionality. This term was first introduced by Kimberlé Crenshaw in a landmark essay title "Demarginalizing the Intersection of Race and Sex: A Black Feminist Critique of Antidiscrimination Doctrine, Feminist Theory and Antiracist Politics." She introduced the term to discuss the marginalization of Black women in both law and politics due to their two identities of being a woman and being Black [47]. Today intersectionality is important to consider in a wide range of settings because no one person has only one aspect of their identity and certain identities are marginalized in our society. For example, a Black, female physicist may have a very different physics experience than a white, male physicist because of both her race and gender identities.

We can also consider identity and what we mean by identity through either a sociocultural or sociocognitive lens. Sociocultural theory in psychology looks at how society contributes to an individual's development, whereas a socio-cognitive lens would mean understanding the mental processes that a person is undergoing [48]. The socio-cognitive approach to identity focuses on self-regulation, which can be influenced by the situation and context. The sociocultural approach, based upon work by Vygostky, is not about the individual's thoughts and motivation, but it is about the social aspect that takes place both externally and internally [49]. In other words, the social situation around a person supports that individual's internalization of ideas and development [50]. Since we are concerned with informal physics groups and how facilitators within those groups experience physics identity, we are taking the sociocultural approach to identity. We are interested in how external factors of the informal physics program impact the individual's identity development.

2.2 Identity in Community

Many different researchers have many different ways of viewing identity and how it impacts the subject of their research. James Gee takes another approach to understanding identity within research. He talks about four different ways to view identity, which he calls nature-identity, institutional-identity, discourse-identity, and affinity-identity [51]. According to Gee, nature-identity consists of the aspects that are naturally a part of someone (such as being left-handed or being a twin) and develops outside of the individual's control. Next, Gee sees institutional identity as an aspect of identity that is given to a person through an institution. Gee discusses his role as a professor as an institutional identity where the institution is the university. Then Gee discusses discourse-identity which is an individual trait (such as being charismatic) that others recognize. Finally, the fourth view of identity that Gee takes is what he calls the affinity perspective or affinity identity. This is an identity that is composed of sets of distinctive experiences and a set of distinctive practices. Gee goes on to describe an affinity group as being made up of people who share an interest and participate in a specific set of practices. This perspective aligns with the idea of a community of practice, a framework developed by Lave and Wenger, that describes a group of people who must share a domain (or set of goals), community, and practices [34-36]. We see our work of looking at physics identity within informal physics environments that act like communities of practice as being most aligned with Gee's description of affinity identity. In our case, the informal physics program is the affinity group or the community of practice. In the next sections, I will go into more detail about what is meant specifically by science identity and physics identity and the Communities of Practice framework.

2.3 Science and Physics Identity

While science identity is not studied as often as other attitudinal constructs like interest or self-efficacy, it is an important way of looking at the prevalent problem within science of the under-representation of many groups, especially groups based on gender and race/ethnicity [52]. In a study by Vicent-Ruiz and Schunn, science identity is defined as “the composition of self-views that emerge from participation in certain activities and self-categorization in terms of membership in particular communities or roles” [52]. They go on to explain that researchers have three different conceptualizations of science identity: 1) Carlone and Johnson discuss a sense of community and affiliation, 2) Aschbacher et al. discuss science identity as being built by consistent extrinsic and intrinsic attitudinal factors, and 3) Archer et al. discuss science identity developing through a match between school science and real science [52].

In 2007, Carlone and Johnson created a model for science identity, informed by Gee's theory of identity. In their model for science identity, they lay out three dimensions to overlap: competence, performance, and recognition [53]. They go on to note that “someone with a strong science identity would rate themselves highly and be related highly by others in each of these dimensions” [53]. They used this model of science identity to study the experiences of 15 successful women of color who are in their undergraduate and graduate studies within science [53]. In 2010, Hazari, et al. drew upon Carlone and Johnson's model of science identity to specifically study experiences of 3,829 students from 34 US colleges and universities within physics [21]. Within their work, they developed a model of physics identity that draws upon the three dimensions laid out by Carlone and Johnson (recognition, performance, and competence). However, Hazari, et al. added in a dimension of interest and looked specifically at physics interests to contextualize the model within the physics experience [21].

A person's discipline-based identity, such as a physics identity, is related to the individual's perceived association with physics [24, 53]. As a sociocultural construct, an individual's physics identity is mediated by their career interests, social environment, cultural norms, and interactions - it is how we are perceived within our disciplinary role, and what resources are available to pursue those interests [54-59]. Therefore, the culture surrounding the discipline and the departments in which we conduct our studies can highly affect our discipline identity. Recent research indicates that a stronger connection with the discipline (i.e. a development of a discipline identity, such as a physics identity) increases the chances of pursuing and persisting in the discipline [21-22, 24]. The majority of studies on science and physics identity have focused on identifying the characteristics that contribute to the formation of a science/physics identity [17, 21] i.e. what are the characteristics of the individual and their experiences that will indicate the formation of a physics/science identity? However, if we define identity as a social construct and the combination of multiple identities, then we also need to understand how the parts develop and interact, what activates the different identities under different contexts, and how the collective impacts and shapes these multiple identities.

2.4 Introduction to Communities of Practice Framework

The Community of Practice (CoP) framework was developed in 1991 by cognitive anthropologists Jean Lave and Etienne Wenger to identify "groups of people who share a concern or a passion for something they do and learn how to do it better as they interact regularly" [35]**.** While the concept of a group working together is nothing new, the term “community of practice” has been coined relatively recently. However, this lens of looking at how groups form and operate has turned out to be very useful to many organizations across a wide range of sectors.

Lave and Wenger were studying apprenticeships as a learning model when they created the term to describe “the community that acts as a living curriculum for the apprentice” [36]. During this time, Wenger identified the common unspoken norms and practices that the individuals have adopted as part of the collective and how moving towards developing expertise in those practices grants the individual seniority within the group. It is through these norms and practices that individuals recognized themselves as part of the collective. Through the individuals' interactions and what they did inside and outside the community, Wenger was able to build an understanding of how they defined membership in the community and what affected that membership [35]. The framework allows us to see past formal structures (such as classrooms or business) that form groups and instead understand how members are engaging with the practices of the group and informal learning happens as a result.

Since its inception, the Communities of Practice framework has been utilized within the fields of business, organizational design, government, education, and other areas [36]. Within business, the framework has been found to have practical applications because performance is often increased when there is a collective knowledge shared among all members. The communities of practice approach allows people to work on recurring sets of problems collectively [38]. Similarly, the communities of practice approach can be useful within government because a collective knowledge and approach to solving complex problems is beneficial [36]. Within education, various organizations such as school districts and professional organizations have adopted the communities of practice approach [36]. However, education research has also found utility with using the framework as an analytical lens. I have included a discussion later in this chapter about the use of the Communities of Practice framework within physics education research.

2.5 Characteristics of a Community of Practice

Communities of practice are groups of people that together engage in a learning process and work towards achieving learning goals. However, not every "community" represents a community of practice. In order to be identified as a community of practice, Lave and Wenger [37] defined three main characteristics (seen in Figure 1): i) The *domain* represents the set of shared interests, passions, and goals. A member of the community actively participates in activities that contribute to these common goals. The domain is connected to the vision of the community, and members of the community share a set of skills and expertise necessary to achieve these goals; ii) The *community* is formed by the members who work towards the common interest and help each other achieve the goals of the group (CoP domain). Therefore, they engage in common activities, build relationships, exchange information and knowledge through interaction, and learn together; iii) The *practice* relates to the sets of tools, principles, norms, language, methods, and resources used to attain the CoP domain, to interact with other members, and participate in the activities. In the context of the broader physics community, some of the practices can be explicit, such as the use of scientific methods; others are more implicit, such as the way physicists use and interpret mathematics compared to other disciplines (often referred to as the hidden curriculum) [60].

We can consider the physics community as an example of a CoP. The physics community (even though there are subgroups based on research topics, projects, departments and societies across the world) can be viewed as a collective that is working toward a common vision to develop a deeper understanding of the universe's behavior (the CoP physics *domain*). Each of the members of the physics community, physicists and physics students, make up the *community* and bring their diverse expertise to achieve that goal.

Figure 1: The three necessary characteristics of a community of practice.

Finally, there is a set of common norms and practices, such as the use of mathematics as a language to communicate nature's phenomenon and the use of scientific methods to approach the validity of a theory or hypothesis (which compiles the *practices* of the community).

In addition to different trajectories, Wenger describes five different levels of which members of the community can participate and how they move between layers [35, 37-38]; the levels of participation within a CoP are dynamic and can change at any time. Figure 2 shows a graphical depiction of what these levels may look like. Members of a community of practice that participate on a minimal level are considered peripheral members whereas the core members of the group are considered insiders. There are many other levels of membership within these two levels. Furthermore, because membership is dynamic, members can move within the levels by moving more toward the core groups (inbound) or moving more toward the peripheral level of membership (outbound). For example, someone with a physics degree who decides to continue on to graduate school would move toward a more insider role within the physics community.

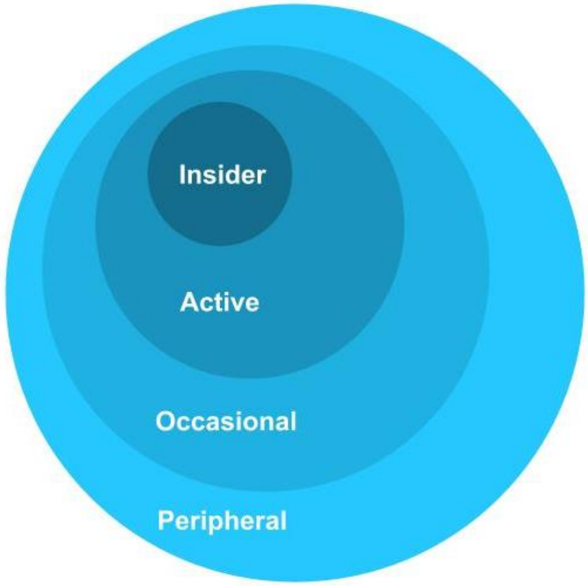


Figure 2: Levels of membership (with peripheral being the most infrequently interacting members and insider being the core group of members). Movement can take place due to the dynamic nature of the levels (outbound or inbound movement).

2.6 Looking at Physics Identity with Communities of Practice

In physics, previous studies have used the CoP framework to study how students and teachers learn and develop physics identities [54-56, 61-62]. Among the more relevant studies that informed the current study are: Close, et al. [55], who used the CoP framework [35] blended with a physics identity framework [21] to look at how university students' physics identity was impacted while participating in the Learning Assistance (LA) program. They used a blended framework to understand the connections between elements of identity; more specifically, they used the CoP framework to determine what were the influential factors within the program that impacted participant's identity. By looking at written materials and interviews with the Learning Assistants, Close, et al. found that the LA program "provides a mechanism to support students in developing integrated physics identities" (p. 17). A different study by Irving and Sayre [56] studied physics identity development within formal learning environments by taking a close look at upper level physics courses through semi-structured interviews with students. They used the CoP framework to determine whether or not the students are showing signs of changes in their membership in the physics community while they participate in different upper division level classes that are central to the physics curriculum. The study found that undergraduate research experiences are legitimate peripheral practices of the physics community of practice [56]. These studies used the Community of Practice framework to study identity formation differently. The first one looked at what elements within a community of practice can promote identity development, while the second one looked at changes in the membership within the community that indicate shifts in identity development. These studies were done either within a formal classroom space or with participants who were a part of a formal classroom space (i.e. Learning Assistants).

2.7 Communities of Practice as a Lens for Informal Physics

Within the studies described in subsequent chapters, I postulated that informal physics programs can support physics identity by functioning as a community of practice for undergraduate and graduate student facilitators. Informal physics activities can range widely in terms of format, frequency, content, audience, and level of involvement of university physics students; thus, it is probable that not all informal physics efforts can be classified as a community of practice. For example, a common type of physics public engagement event is popularized lectures aimed at high school students or adults. Often these lectures are given by individual faculty with little extended involvement from university physics students or others within the department - it is less likely that these efforts could be considered communities of practice due to the nature of the activity and limited ways individuals are involved. In contrast, I am particularly interested in informal physics efforts that involve many members all working toward the same goal.

Due to the shared knowledge that the student facilitators have while participating in informal physics spaces, the Communities of Practice framework can be a useful lens of understanding group dynamics and the interactions of members. Through participation over time, students may become more central members of the community; alternatively, if their level of commitment lessens, they may become a more peripheral member. Additionally, someone who has enjoyed participating and expresses the desire to continue participating in a certain community would experience identity development toward more central membership within the community (inbound), while someone who is not as deeply involved in the core activities may not experience this shift in identity (neutral or peripheral).

In our work, we seek to understand if informal physics programs function as CoPs and to look at how student experiences impact their identity development. To do so, we need to see how the constructs described by Lave and Wenger make sense in the context of informal physics programs. In the first study, we operationalize all of the constructs within the Communities of Practice framework using two different informal physics programs. In Chapter 4, I detail the three aspects of these two programs that allow them to be considered Communities of Practice. Our second study (Chapter 5) utilizes the operationalized Communities of Practice framework to understand how facilitators in three different informal physics programs (Science Theatre, PISEC, and Quavers to Quadratics) are impacted through the different formats of the programs (and a detailed description of how each of these programs is a Communities of Practice is included). Finally, later studies utilize the Communities of Practice framework to explore how programs that combine physics content with art can support the development of physics identities among those who may not see themselves as a traditional physicist (Chapter 6).

2.8 Summary

Within the study, we sought to understand if informal physics spaces can be characterized with the communities of practice approach and how individual's experiences in these informal programs can impact their identities. Due to the nature of informal physics programs (there can be many facilitators, certain demos or activities typically used, and groups have unique ways to interact with the audiences), the Communities of Practice framework is a good candidate to help us understand the experiences within these programs. Additionally, since we are interested in how an experience can impact an individual's physics identity, a qualitative approach where we can learn about the individual's experiences through observations and interviews is appropriate. In the next chapter, I will go into further detail about the design of our studies, the rationale for those design choices, and the implications of our methodologies.

CHAPTER 3: STUDY DESIGN

In this chapter, we describe the methods used to operationalize and contextualize the CoP framework to determine membership within a community and the mechanisms that affect identity within informal physics programs. In alignment with the constructivist nature of the Community of Practice framework [35], we have chosen to holistically look at informal physics programs through program observations, artifact analysis, and using qualitative methodology (interviews) as a way to capture the meaning of the stories shared by the university students who facilitated an informal physics program. Through the observations, program information, and facilitator narratives we can identify the important aspects of their experiences of becoming physicists and facilitating the program and how these aspects intertwined.

Using this approach of multiple data sources is appropriate for this dissertation because it allows us to understand the in-depth experiences of informal physics program facilitators in the context of the whole program. Using this approach, as opposed to a quantitative approach, allows for this study to look at the complex phenomena of how facilitators within informal physics programs experience identity development. This dissertation includes data from four distinct physics programs: Science Theatre, PISEC, Quavers to Quadratics, and Bohring Art. First, we contextualized the CoP framework within the context of two informal physics programs, Science Theatre and PISEC, in order to operationalize the CoP framework. Once we created the framework with constructs that make sense within an informal physics context, we applied that framework to additional data, including a larger sample of facilitators from three programs, the two previously used programs and another called Quavers to Quadratics. Finally, we were interested in how the CoP framework could be used to look at identity development within a program that intentionally combines physics and art, called Bohring Art. Within this chapter, the constructs of the CoP framework are introduced, the study design is detailed, a brief overview of all four informal physics programs is provided, information about the interview process is provided, and a discussion about the analysis methodology is included. Chapters 4, 5 and 6 will then describe the results of the operationalization and the application of the framework to the programs.

3.1 Constructs of Communities of Practice Framework

Lave and Wenger described two main parts to an individual's membership in a community of practice: competence and identity [35]. The set of constructs that describe competence within the community (referred to here as Community Dimensions) determines positionality and movement among membership levels (seen in green in Figure 3). The set of constructs that describe identity within the community (referred to here as Mechanisms of Identity) establishes what impacts the level of membership that an individual experiences within the community of practice (seen in pink in Figure 3). We describe these constructs in more detail below.

3.1.1 Community Dimensions

An individual's membership in a community of practice is affected by their competence in the domain and practices of the community. For any particular community of practice, an individual's competence is defined by the community and what it values through engagement and participation. There are three dimensions of competence for a community of practice: Accountability to the Enterprise, Mutuality of Engagement, and Negotiability of the Repertoire (referred to as Community Dimensions in Figure 3). These dimensions were set forth by Lave and Wenger. The dimensions of competence become dimensions of identity in the sense that they help determine the degree of membership of the individuals within a CoP. That is, a competent member

- a central member of the community - has high levels of achievement within those three dimensions.

The Accountability to the Enterprise construct is related to the idea that the CoP must have a domain or some shared goal or mission that members are pursuing. In terms of members of the community, this idea is related to what they value and do based on their membership. Accountability considers how they understand the goals/objectives of the community, how they take responsibility and embrace those goals, how they contribute to the achievement of those goals, and their constant negotiation and redefinition of the goals. Within the physics community, this could be a student learning more about current research within the field and understanding what topics are important to physicists.

The Mutuality of Engagement construct is related to the idea that the CoP must have a community or sense of members exchanging ideas and information. This dimension establishes how members interact with other members in the community, and it is the basis for identity through participation. Included here are how members engage with other members to establish relationships within the community. Within the physics community, this would be the interactions that people have, such as how a postdoc may mentor a graduate student within their research project.

The Negotiability of the Repertoire construct is related to the practice aspect of the CoP and how members work together to achieve the group's goals. This construct is related to the history and experiences created through negotiation and engagement with other members of the community. Related to identity, this construct translates into a personal set of events, references, memories, and experiences that create relations of negotiability with respect to the repertoire of the practice. Members may think about their ability to use skills, language, and resources of the practice to engage with the community. Within the physics community, they could include a student learning how to use and understand different pieces of lab equipment through their advanced lab course or through a research project.

3.1.2 Mechanisms of Identity

Apart from the dimensions of competence (community dimensions), Lave and Wegner also identified different categories that link community of practice to identity. These categories determine what experiences within the community of practice help one become a more competent, central member of that community. Those categories are: Negotiated Experiences, Community Membership, Learning Trajectories, Nexus of Multimembership, and Relationship between Local and Global. Negotiated Experiences is related to recognition, being identified by other members of the community and sharing the values of the community. Community Membership is related to the interactions of the members through the practices and shared repertoire of the community. Learning Trajectories is related to experiences, past, present, and future that influence or participation in the CoP. Nexus of Multimembership is related to how we participate in more than one community. Finally, Relationship between Local and Global is about how more central members of a community of practice are able to develop a sense of belonging within that community, but also reflect on how that fits into the broader world. For example, participating in a local science outreach program may allow someone to understand more about the national need for more women and people of color within the sciences.

3.1.3 Operationalizing the CoP Constructs

Chapter 4 details how we operationalized the CoP framework in the context of informal physics programs. A summary of the Community Dimensions codes, the operationalized definitions, and examples from the data are shown in Table 2 in Chapter 4. Similarly, Table 3 shows the operationalized definitions of the Mechanisms of Identity along with examples from the data. In addition, members of the community of practice may experience movement between their levels of membership (inbound, neutral, outbound) or may be situated at a certain level (insider, peripheral). Chapter 4 describes the additional subcodes that indicate membership level or movement between levels of membership (shown in Figure 9 which expands upon the framework shown in Figure 3).

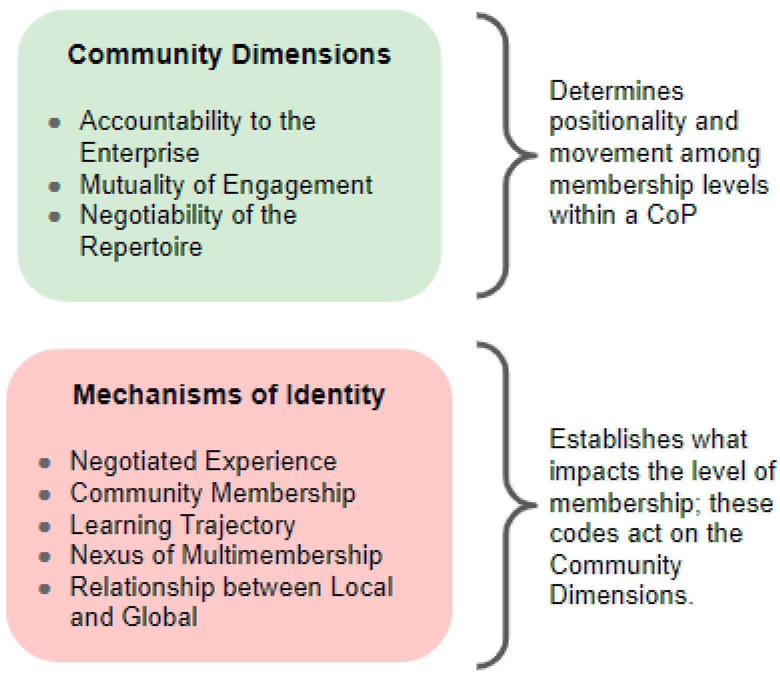


Figure 3: Summary of Community Dimensions and Mechanisms of Identity constructs.

3.2 Study Overview

When designing this study, we first looked to the Communities of Practice framework constructs that are outlined above to understand how they might help us investigate informal physics experiences. In order to use the framework, we needed to operationalize the constructs so that they would be something useful for our later studies and for others who would like to take this approach. When I say “operationalization,” I mean that we are taking a theoretical framework with broad concepts and unpacking it in the context of our work, informal physics programs. The operationalization process includes defining what each name construct means in our context. This was the bulk of the first study (discussed in Chapter 4) and involved many conversations among the research team to create definitions that are meaningful and can be applied to the data.

When we set out to operationalize the Communities of Practice framework, some decisions had to be made about what kind of data would help us understand the meaning of the theoretical constructs. We needed data from informal physics programs that would help us understand what “accountability” means, what “enterprise” means, what “mutuality” means, etc. With quantitative data, we would have a statistical picture of the programs, but we would not know about what was happening “under the hood”. So, we needed qualitative data about the programs, i.e. descriptions of the experience of participants, observations of the participants, and documentation of group knowledge. We therefore collected a variety of data sources including:

- Interviews with program facilitators (i.e. undergraduate and graduate student volunteers)
- Interviews with program leaders
- Observations of facilitators interacting with audiences
- Observations of facilitators planning activities
- Documentation of program activities (websites, photos, information wikis)
- Institutional knowledge from members of the research team being members of the informal physics program

However, in this work we use interviews as the primary data sources because we are interested in understanding the identities and perceptions of informal physics program facilitators.

Facilitators' explanations of lived experiences through group membership and interactions with other group members illustrate how they perceive their identities have been affected by their group membership. The general approach to the work presented in this dissertation, shown in Figure 4, involves observing representative program activities, collecting data, operationalizing the CoP framework with a few interviews, and applying the contextualized CoP framework to all of the collected interview data.

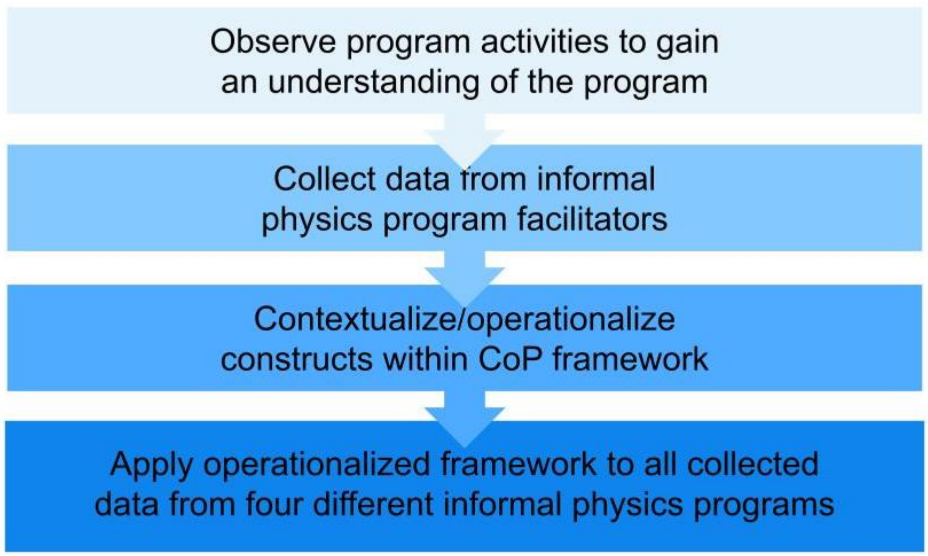


Figure 4: A basic overview of the process taken within this dissertation.

3.3 Study Context

For this dissertation, data was analyzed from four different informal physics programs. The programs selected for full application of the operationalized Communities of Practice framework are Science Theatre (based at Michigan State University), PISEC (based at the JILA Physics Frontier Center at the University of Colorado Boulder), and Quavers to Quadratics (a collaboration between University College Dublin, Trinity College Dublin, and the Irish National Concert Hall).

All three programs were chosen because they have large numbers of physics student volunteers, have been active for a number of years (Science Theatre since 1991, PISEC since 2008, and Quavers to Quadratics since 2014), and have close links with university physics departments. Furthermore, the design, content, and implementation of the three programs provide a range of formats, from the more common (demonstration show) to the more novel (blending physics and music). They also range in their involvement of physics students, as well as the different types of students, with one group being entirely organized by undergraduate students (Science Theatre), one group being mostly physics graduate students (PISEC), and one group bringing physics students together with music and education students (Quavers to Quadratics). Thus, these three programs allow us to gain insight into a wide, international variety of informal physics programs that utilize university students as facilitators within the program. The fourth program examined in this dissertation, Bohring Art, combines physics and graphic design concepts. The CoP framework is used to examine if and how a CoP forms throughout the life of the program. Bohring Art is included because of the unique approach to combining physic and graphic design concepts but also because I was involved in both the planning phase and bulk of the program.

Additionally, an important consideration in the selection of programs was that at least one of the authors has been, or is currently, a practitioner associated with a program in some capacity. Our direct knowledge of these specific programs served to validate the selection of these programs as candidates for communities as practice; it further acted as a validation measure for data analysis [63-64]. Another affordance of our practitioner experiences is that they provided us with insight in our interpretation of how the community of practice analysis connected with the structures and norms of programs.

Each program will be discussed in detail in the later chapters, but a brief overview of each program is presented here. Throughout each description I note which aspect of the group is the domain, community, and practice.

3.3.1 Science Theatre

Science Theatre is an outreach program through Michigan State University that consists of undergraduate and graduate students that perform science demonstrations and stage shows. We investigate membership ideas and the relevance of the communities of practice framework within this group. Funding for Science Theatre comes from the physics department and their aim is to "get children and adults alike excited about the wonders of science" (*domain*) [66]. In order to carry out this goal, the group has developed a variety of physics and other science demonstrations that are used either on stage (generally for an audience of local K-12 students) and hands-on environments (i.e. at the MSU science festival or at local K-12 schools). Most of the outreach events are one-time and between around 1-2 hours in length. Students in the group can choose to participate in as many of the one-time events as may fit in their schedule. The group is composed of 40 student volunteers from a variety of STEM majors, some of whom have officer roles, a staff coordinator, and a physics faculty advisor (*community*). The group organizes itself in a large multi-room workspace found in the basement of the MSU planetarium to store equipment, create and test new demos, and to socialize (*practices*).

One unique aspect of Science Theatre is the opportunity for members to participate in an intensive outreach experience during a spring break trip through rural areas of the state. For this week-long trip, members of MSU's Science Theatre can choose to volunteer to drive demonstration equipment to northern rural Michigan. While there, they put on a multitude of stage shows at K-12 schools who have limited connection with universities. They spend that week, Monday through

Friday, traveling from school to school in 3-4 person teams to complete presentations during the students' school days. Once the shows are done for the day, the teams reconvene to eat dinner, debrief on the day, and can choose to interact further to pass time. Nine students (eight undergraduates and one graduate) volunteered for the 2018 spring break trip in which students performed these stage shows at more than 60 schools. Figure 5 shows a collection of pictures that were taken by Science Theatre members that participated in the trip during 2018.

Figure 5: A collection of photos taken by Science Theatre members on the week-long trip to the Upper Peninsula of Michigan.

3.3.2 Partnerships for Informal Science Education in the Community (PISEC)

PISEC (Partnerships for Informal Science Education in the Community) is an after-school program, where physics students work with children to explore fun, hands-on physics activities. This program is the main public engagement effort of the JILA Physics Frontier Center for Atomic, Molecular and Optical Physics at the University of Colorado Boulder. (Collaborator Claudia Fracchiolla and research advisor Kathleen Hinko have served as program directors.) The main goal of PISEC is to give children the opportunity to explore pathways to physics and other STEM careers by engaging them in interactive, inquiry-based physics activities. PISEC also seeks to improve the pedagogical and communication skills of university physics students (*domain*) [67]. It runs each semester with 15-20 volunteers who are mostly physics graduate students. Volunteer facilitators meet with elementary and middle school children once a week for an hour at the children's school (*community*). During that after-school hour, the children are encouraged to engage in scientific practices through proposing hypotheses, designing their own experiments, and reporting their findings and ideas (*practices*). Figure 6 shows a collection of images from the after school interactions that take place in PISEC.

Figure 6: A collection of photos from the afterschool activities that PISEC facilitators participate in with local students.

3.3.3 Quavers to Quadratics

Quavers to Quadratics is a program for school children to play with ideas common to physics and music [68]. The children (typically 8 to 12 years of age) are led in their play by undergraduate students from physics, music education, and science education. Quavers to Quadratics is a collaboration between a national cultural institution (the National Concert Hall) and two universities in Ireland. University students from three departments (physics, science education, and music education) at the corresponding universities participate in the program. One of the aims of Quavers to Quadratics is to have a creative space for undergraduate students to play, work with others from outside their disciplinary niche, and to gain teaching experiences such that they might reflect on their view of physics, music, and education (*domain*). The program runs twice a year with 15-20 undergraduates a semester, who are paid for their effort (*community*). Each three-month cycle requires the undergraduate students to co-plan, co-teach, and co-reflect upon two initial classroom visits at the children's school, a day-long workshop at the National Concert Hall, and a final classroom visit. In these interactions, facilitators encourage children to explore questions like “What is a wave?” “How does frequency and amplitude of a wave affect sound?”, and “How do the shapes and sizes of musical instruments affect sound?” (*practices*).

Figure 7: (Left) Children learning about string instruments during the one-day workshop at the National Concert Hall and (right) students and Quavers to Quadratics facilitators discussing orchestra composition.

3.3.4 Bohring Art

The Bohring Art project team consisted of four undergraduate students, a physics graduate researcher, a physics postdoctoral fellow, and two faculty members, one in physics and one in graphic design (*community*). The physics students were selected from a pool of twenty students who applied for the advertised summer project through the Department of Physics and Astronomy at Michigan State University. Six assessment categories were considered in the rubric: research experience, community/outreach/artistic activities engagement, resume and statement quality, and programming skills. The design students were selected from the pool of students who attended the Interactive Design class during spring 2020. Within the project, the students chose to create a website that would employ the use of art and graphic design to teach physics to the public (*domain*). The students created a narrative that provides the user with the goal of observing stellar phenomena using their own virtual space telescope. The website leads viewers through four activities each with different types of interactive components designed to simulate experimentation, and the design of these activities was decided throughout brainstorming sessions. Figure 8 contains screenshots from the finished website. This project was completed entirely during the COVID-19 global pandemic; therefore, the students met remotely. A software platform was used to create a wireframe of the website, the Slack messaging application was used for quick and frequent communication, and Zoom was used to discuss and present their ideas. They discussed aspects of the website and taught each other about the physics and graphic design concepts that were needed (*practices*).

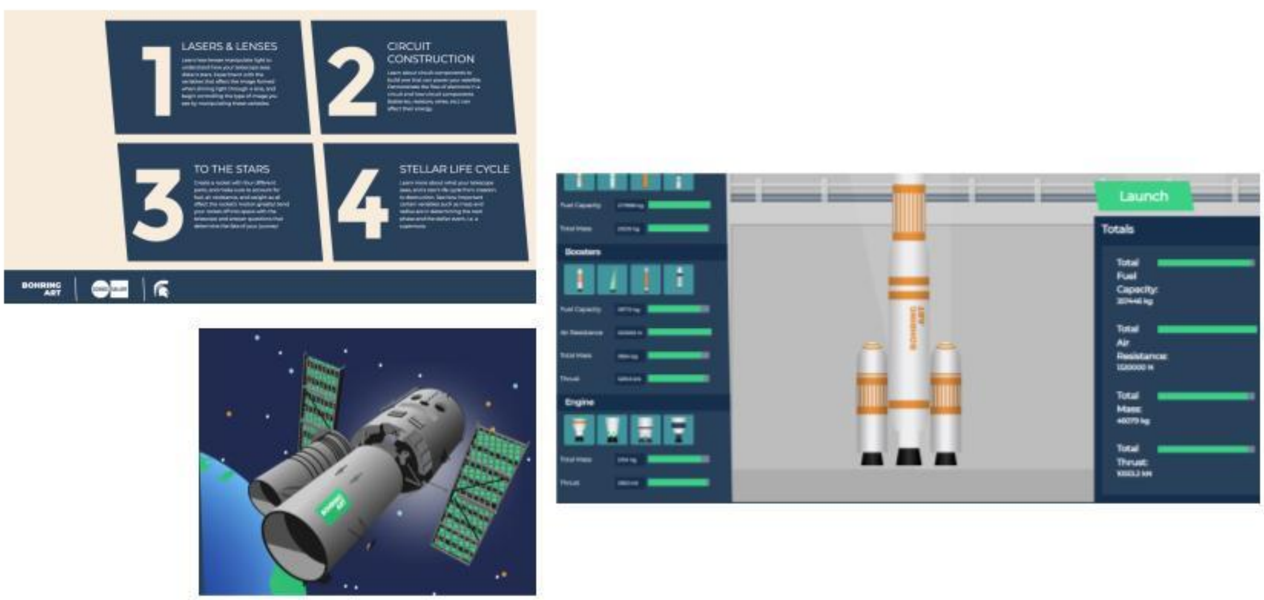


Figure 8: Screenshots from bohringart.com [69].

3.4 Interview design and participant demographics

In this work, we used semi-structured interviews to collect data from participants from four different informal physics programs (all interview protocols can be found in Appendix A). This form of interview is a common data collection method used within qualitative research and consists of open-ended questions that allow for more discussion to take place between the interviewer and interviewee [70]. Using a semi-structured interview approach allows for the data collection to be versatile and flexible which can ultimately lead to better quality data. The structure of a semi-structured interview starts with the researcher preparing an interview protocol with the main questions that will guide the interview. This protocol may also include some possible follow up questions that can be asked depending on what the interviewee discusses. However, a semi-structured interview allows the interviewer to ask follow up questions that make sense in the moment based upon the conversation.

Interviews were collected from program facilitators, either undergraduate or graduate students from the four informal physics programs. Depending on the structure of the program, participants were interviewed either once or twice. Each interview focused on similar themes but had specific questions about program activities.

For the three informal physics programs discussed in Chapters 4 and 5, more data was collected than is presented in this dissertation. We collected interviews from 58 participants across the three informal physics programs. These participants were from the pool of those facilitating the activities in the programs and that were willing to participate in the research study. Based on a careful reading of all interviews by multiple members of the research team, we focused on a subset of 18 participants, which correspond to 29 total interviews. The reason for this selection was threefold: (i) identify the interviews that had descriptive information—some of the interviewees did not provide detailed answers which limited what we could learn from their experiences; (ii) allowed similar representation from the three programs because we had many more interviews from one of the programs than the other two; and (iii) we selected interviews that reflected facilitators' identities in terms of gender, race, and academic status (undergraduates, Ph.D. students, and postdoctoral fellows)—and that the representation in those categories reflected some of the demographics of each program. Seven participants were from PISEC (7 interviews), five participants were from Science Theatre (10 interviews), and six participants were from Quavers to Quadratics (12 interviews). There are several justifications for using a subset of the full data set for analysis: (1) Consistency of interview protocols—earlier versions of the PISEC protocol differed from the protocols used for the other two programs, because we used PISEC participants to test the different protocols. We conducted three different test rounds of the protocol before arriving at the final version, which is the one used in this study and (2) interviews used in earlier stages to operationalize and validate the framework were excluded from the current study. Each interview within our entire dataset was read, or listened to, by members of the research team and the final interviews selected for this paper were intentionally chosen to represent the diversity of the facilitator population within the programs. Table 1 summarizes the number of interviews and participants for each program that were used in the analysis. Facilitators were not asked other demographic categories (i.e., disability status, sexual orientation) and therefore cannot be reported. Below is a brief description of the interview process for each program, including the demographics of both the interviewer(s) and interviewees (information was collected directly by asking each person how they identified).

Table 1: Summary of some interviewee demographics for the four programs that are examined in this dissertation.

Program Name	**Educational**	**Number of**	**Gender Identity**	**Race/Ethnicity**

	Status	interviews	(self-reported)	(self-reported)
Science Theatre	5 undergraduate students	2 interviews each (pre-/post-trip interview)	4 males, 1 female	5 identified as white and one identified as Black
PISEC	1 undergraduate, 1 postdoc, and 5 graduate students	1 interview each	4 males, 3 females	6 identified as white, 1 identified as Asian
Quavers to Quadratics	6 undergraduate students	2 interviews	3 males, 3 females	All 6 identified as white (Irish)
Bohring Art	4 undergraduate students 2 facilitators, one postdoc and one faculty member	2 interviews from each undergraduate student (pre-/post- summer) One interview from each facilitator (post-summer)	Undergraduate students: all male Facilitators: both female	Undergraduate students: 3 identified as white, 1 identified as Black Facilitators interviews: both identified as white

Interviews were conducted locally, that is, the researcher conducting the interview was, at the time of the interview, based in the institution where the program is hosted. The large majority of the interviews were conducted in person using audio recordings. The length of the interviews varied between 30 minutes to an hour, depending on how much detail the interviewee gave in the questions and some of the variations in the protocol.

3.5 Researcher Positionality

I would like to make a note of the identities of the researchers involved with this study, including and especially myself; as with any study involving human interpretation, the identities of the researchers are important aspects of possible bias among the study design. I am the author of this dissertation, and the primary researcher for the studies described in the following chapters: I identify as a white female. The interviews presented here were conducted by two female physics education researchers, a Latina woman and an African American woman, who were also involved in the informal physics program. Their involvement and experience with this informal physics program allowed the two researchers to further the discussion during the interviews and ask probing questions about specific aspects of the program. Other researchers, including myself, who contributed to the analysis are white. Additionally, two of the researchers involved in the work in this dissertation are past program directors of PISEC, which means that they also bring a CoP central member perspective to the contextualization and operationalization process. These experiences allow those authors to provide insight that is useful in the interpretation of each interview; however, it may also provide a source of positive bias towards the program. We have tried to mitigate this potential bias through bringing on researchers from different institutions for analysis.

3.6 Interview collection

There were three variations of the protocol, each adapted to the corresponding program. However, all three were centered on questions about the student facilitator's motivations for participating in the programs, the expectations and hesitations regarding volunteering, as well as how the students identified themselves regarding their degree. The differences in the protocols consisted mainly of questions pertaining to the particular practices and/or activities of the relevant program. Other differences in the protocols arose from the time when the interview took place. For example, some students were interviewed once - after they had participated in the program for at least one semester, while other students were interviewed twice during their participation in a program. This difference in frequency and timing of the interviews was mainly due to the nature of the programs. For example, two of the programs require a semester-long commitment (PISEC and Quavers to Quadratics) whereas the third program (Science Theatre) allows for students to participate when time allows. Also, two of the programs, Quavers to Quadratics and Science Theatre, offer a week-long trip during spring break or summer break. In the event that one student had completed two or more interviews, we viewed the collection of interviews as a snapshot of the student's relationship with the program.

Science Theatre: Participants were interviewed twice, once before a weeklong trip and once after. Before asking for trip participants for an interview, we arranged to attend one of the scheduled pre-trip meetings. During this meeting, Science Theatre members were discussing details of the trip and going over how to perform some of the more complex science demonstrations such as bed of nails and burning money. Members were able to try out performing the demonstrations and offer advice to newer members who would be participating in the trip. At the end of the meeting, we described our study and asked those who would be willing to speak with us to write down their email. An email was sent later that week to interested participants to schedule the first interview. All pre-trip interviews were completed during the week before spring break. After spring break, an email was sent to all interested participants asking to schedule a follow up interview. All post-trip interviews were scheduled during the two weeks following spring break. For Science Theatre interviews, the interviewer was a white, female, graduate student. All five interviewees were undergraduate students. One out of the five identified as a female and one out of the five identified as a person of color. The semi-structured interviews followed a pre-trip protocol that focused on competence related to their involvement with Science

Theatre, future career plans, and expectations of the trip. The post-trip protocol focused on feelings about the trip, specific demos performed, and the impact of going on the trip.

PISEC: We designed a semi-structured interview protocol that asked participants to discuss their experiences in the program and their perceptions toward physics and informal physics programs. Examples of the questions include: Why did you decide to volunteer for the informal program?, In what ways has participating in the informal program benefited you?, What have you gained from those experiences?, What is the most important thing you got out of them?, How did you end up in physics?, Do you identify as a physicist?, and What were the most important factors that landed you in physics and what motivates you to continue? The semi-structured interviews allowed us to have the freedom to follow up on questions and be able to capture as much of the narrative as possible. Interviews were conducted by two researchers and lasted about an hour on average. We want to understand their stories about their journey of becoming physicists, and what led them to engage in informal physics.

Quavers to Quadratics: Semi-structured interviews of nineteen facilitators were conducted during January 2019 Quavers to Quadratics workshops (6 sets of two interviews each were analyzed for this work). Interviews were conducted by a white, female researcher, lasting on average twenty-nine minutes. Interviews were designed to learn about students' motivation for participating in the program and their discipline. Some sample questions included: “Why did you decide to join the program?”, “Did you have any hesitations about joining the program?” and “How would you describe a typical physicist/musician?” The interviewees were pursuing a variety of degrees: Music Education, Physics, or Science Education.

Bohring Art: Students were interviewed once at the beginning of the 10-week summer project (in the first week) and once at the end (in the tenth week) by the same researcher. The first interview focused on prior experience and expectations for the project while the second interview captured the experiences of each student. The identities of the two researchers who collected and coded this data set are a white, female graduate student who collected all the data and also worked with the other researcher to code and analyze all of the data. The second researcher is a Black, male undergraduate student who worked to code the data. Each researcher participated in the Physics/Art project, either as a graduate researcher or as an undergraduate physics student, and continued to work on the research aspects of this project after the conclusion of the summer. The involvement that both researchers had with the project over the summer provided unique insight to the data.

3.7 Interview Analysis

All interviews were coded using MaxQDA. The interview coding process required many members of the research team and was carried out in two main phases: a training and validation phase (where only a few interviews were coded) and an independent coding phase (where the remaining interviews were coded). This two-phase approach allowed us to ensure that each member of the research team understood the framework and felt comfortable coding the interviews. In addition, this phased approach allowed us to utilize inter-rater reliability to ensure that the coding was consistent among all of the interviews and that the codebook could be used by other researchers.

The first phase of the coding process was focused on validation of the codebook and training each member of the research team (mainly covered in Chapter 4). First, we had two members of the research team independently code an interview for one program with a set of codes (*Community Dimensions* or *Mechanisms of Identity*) without the subcodes or communities. The team focused on coding complete ideas and were not too concerned about chunk size. For example, a code could vary in length from a few phrases to two sentences if the same idea was being discussed. Then, the researchers compared their coding in order to discuss and reconcile any differences. This part of the process was meant to check how every part of the interview was coded, not only which codes were used but also the length of the coded segments. If there was a discrepancy about the code used, then there would be a discussion in which each researcher would explain why the corresponding segment was assigned the particular code. Throughout this process, we updated and created a robust codebook with our operationalized framework (the full codebook can be found in Appendix B). Once each of the researchers had a good understanding of the coding framework, a second interview was coded independently. The researchers then compared the codes and estimated kappa value for the interrater agreement value. Once agreement of over 80% accuracy had been reached, then the researchers independently coded the interviews with the corresponding subcodes and communities. The same process for coder agreement was conducted for each program and for each set of researchers. Cohen's kappa values can be found in Appendix C.

The second phase of coding was planned to ensure that all interviews were coded and that there was discussion between the researchers during this process (mainly Chapter 5). First, we split into teams so that all six of the researchers coding would only focus on one set of constructs (i.e., each researcher only coded for the *Community Dimensions* or the *Mechanisms of Identity* during this phase). Each researcher was in charge of a set of interviews for coding with the corresponding set of codes and independently coded those interviews. Their partner would then independently code one of the interviews in the set with the corresponding codes to check for interrater reliability. If differences arose, those were discussed with an external researcher member overviewing the process, and the differences were reconciled. Once agreement was more than 80% accurate than the rest of the coded interviews are reviewed by the partner without having to code independently the interview. This team approach allowed us to ensure that all of the interviews were coded in a timely manner and that interrater reliability was checked for each researcher.

CHAPTER 4: FINDINGS FROM OPERATIONALIZING THE COMMUNITIES OF PRACTICE FRAMEWORK TO THE CONTEXT OF INFORMAL PHYSICS SPACES

In order to use the Communities of Practice framework to better understand informal physics programs, we needed to have a way to apply the framework to the qualitative data. This was done by operationalizing the framework so that we had a codebook of all of the constructs from the framework and what they mean in terms of an informal physics program. Much work, resulting in 4 published papers, went into this process [63-65, 72]. For the sake of space and readability in this dissertation, I will first describe the process, and then use the remainder of this chapter to go into depth about operationalization of the framework with data from two of the facilitators (graduate students who volunteered in PISEC). After the in-depth description of personal experiences of two PISEC facilitators, I will discuss some similarities and differences that were seen between PISEC and Science Theatre participants to offer an alternative perspective.

4.1 Scope of work that went into operationalization process

To start this work, we first used two sets of interviews from facilitators in Science Theatre (n=4 interviews). We looked at the Community Dimensions constructs and multiple researchers tried to code the two interviews. Extensive discussion took place between myself, my advisor, and two postdocs who all coded the interviews. We discussed the nuances of the constructs, wrote definitions for what each Community Dimension construct meant for an informal physics program, and selected examples from the interview. This work was written up as a Physics Education Research Conference proceedings paper. Next, we used interviews from two participants in PISEC (n=2 interviews) to do a first operationalizing the Mechanisms of Identity constructs. This process was similar to the process for the Community Dimensions. This work was published as a longer proceedings paper and later included as a chapter in a book titled *Research and Innovation in*

Physics Education: Two Sides of the Same Coin. After understanding the Community Dimensions and Mechanisms of Identity in the context of each program, we further refined the codebook by coding each of the 6 interviews with the full coding scheme (so that each interview was coded with both the Community Dimensions and the Mechanisms of Identity). This work of coding all 6 interviews fully resulted in another Physics Education Research conference paper and a full-length Physical Review article (which is presented in this chapter).

4.1.1 Facilitator participants in this chapter

The remainder of this chapter describes the experiences of two PISEC facilitators. In order to understand their personal experiences within an informal physics program, we applied both the Community Dimensions and Mechanisms of Identity to their interviews. We picked these two stories, from our analyzed data set, to demonstrate the use of the CoP framework to understand how the experiences of facilitating informal physics programs can support the development of their physics identity.

Although we used data from four students and two programs as the basis for operationalizing the framework, this chapter is limited to the stories of the two PISEC facilitators. The two cases we have chosen to describe are white male and female graduate students from the PISEC. These cases were selected for several reasons: as graduate physics students, they have already developed some form of physics identity, and thus we can observe if and how the CoP framework captures identity development or change through participation in the informal physics program. White men are the highest represented demographic in the physics field while women are among the underrepresented groups in physics, and it is important to demonstrate that CoP applies to both their experiences. Furthermore, their individual stories are well representative of the struggles that white women experience in physics, compared to white men. We have chosen to pick two students from a single program to make it easier to compare their experiences being part of the same community of practice - however a serious limitation of this choice is that we do not highlight the voices of students of color from our operationalization process or broader data set.

4.2 Coding process for operationalization

In this study, we operationalize the CoP framework to determine membership and mechanisms that affect identity within the context of informal physics programs. In alignment with the constructivist nature of the Community of Practice framework [37], we have chosen to use narrative inquiry [73] as a methodology to capture the meaning of the stories shared by the university students who facilitate informal physics programs. Through their narratives we can identify the important aspects of their experiences of becoming physicists and facilitating the programs and how these aspects intertwined. We used the analyzed interviews to define the constructs of the CoP in the context of informal physics programs as well as the specific subcodes that emerged from the operationalization process.

For the process of operationalizing the framework, we used purposeful sampling [74] - that is we selected cases from our participant pool that presented different and contrasting perspectives on their experience within physics and the informal program they facilitated. Some of the contrasting perspectives we considered when selecting interviews were: stage in academia (i.e. graduate students vs undergraduate students), gender identity, type of academic institution, struggles in their career development, and choice of physics major vs non-physics major. The main reason for this approach was to explore whether CoP constructs could differentiate between the differing experiences and program structures. From our larger sample, we identified four UEs that had enough variance and similarities to help us contextualize the individual CoP framework constructs [63, 75-76]. We selected two graduate physics students, female and male, both white, who participated in PISEC, and two undergraduate students, a black female physics major and white male non-physics major, who facilitated Science Theatre.

To operationalize the CoP framework, we engaged in an iterative coding and validation process, focusing on two groups of the CoP framework (community dimensions and the mechanisms of identity, described in the following section) in order to establish how and what affects physics identity formation within informal physics programs. We started coding transcribed interviews with Wenger's [35] definitions of CoP constructs, while also coding for emergent themes. First, two researchers coded portions of the interviews independently and developed a codebook with working definitions for the CoP constructs. Through multiple rounds of discussions and additional coding of all four interviews, the codebook was refined and discrepancies were resolved. A third researcher then independently coded the interviews using the codebook and compared results with the other two researchers to guarantee that kappa values were larger than 0.8 was on all the codes. Further validation came from four additional undergraduate researchers through their application of the operationalized codebook to the larger sample. Additional refinements were made based on their feedback. In the next section (and in Figure 1) we describe in detail the CoP constructs, our operationalized definitions, and examples from our data for informal physics education contexts.

4.3 Context

The stories described in this manuscript to illustrate the operationalized CoP framework are of two university students participating as educators in the PISEC after school program. (More information about PISEC can be found in Chapter 3). In this work, we postulate that PISEC is a CoP that has the potential to support the physics identities of its members. From our knowledge of the PISEC program as past practitioners (and via information gathered on the PISEC website, observations of the activity sessions, and conversations with facilitators, staff members, and the current director of the program), we can identify the three essential aspects of a CoP within PISEC - *domain*, *community*, and *practice*. Considering both University Educators and youth as members of the CoP, all participants share the common goal (*domain*) of increasing excitement and exploration of physics through inquiry-driven activities designed for the youth. *Community* is formed by the UEs and youth choosing to come together weekly over the course of multiple semesters. Due to the nature of the program, each group of youth and facilitators are consistent each week, which allows for a long-term development of rapport, communication, and growth to take place within the group. They engage in the *practices* of doing physics through a wide range of fun, hands-on activities. We hypothesize that participation in the weekly sessions can be highly impactful to the identity of those that choose to volunteer as a UE.

Throughout the remainder of this chapter, I will describe how the Communities of Practice framework has been contextualized for informal physics programs, highlighting the cases of two University Educators who were facilitators within PISEC. For the sake of anonymity, we changed the names of the interviewees and removed information that could make them identifiable. The first interview participant, Cecilia, is a female, third year PhD physics student that had just completed her first semester facilitating in PISEC at the time of her interview. She had previous experiences facilitating informal programs. Cecilia started her physics PhD at a different institution abroad but decided to take a different path within the first year and resumed her PhD a year later at the university where she completed her undergraduate degree. The second interview participant, Mike, is a first year male PhD physics student, who had just completed his second semester facilitating in PISEC at the time of the interview. Mike had not had any experience facilitating informal physics programs prior to participating in PISEC. However, unlike Cecilia, he had a direct path from to college and to the PhD program.

4.4 Structuring the Community of Practice Framework

The Community of Practice framework demarks a unit of analysis for which Wenger lays out the characteristics that define it, how it evolves, and its practices; here we describe how we operationalize constructs from CoP theory and then give examples from Mike and Cecilia's stories. Wenger characterized how the practices of a community can shape identity formation, i.e. he identified a set of mechanisms and structures within the communities of practices that can foster the development of an individual's identity through participation. This formation of identity or membership is a dynamic process that is constantly being negotiated. For this reason, CoP theory explains that membership can take different trajectories which determine how the individual chooses to participate in the community [35]. First, we go into more detail in defining specific constructs of CoP theory that allow us to determine trajectories of individuals within a community of practice. In later sections, we show that applying CoP theory allows us to understand individual identity development (for Mike and Cecilia) through membership in a collective social context (the informal physics program PISEC).

Figure 9 is an expanded version of Figure 3 from Chapter 3 and shows how we have approached structuring CoP theory with the addition of subcodes that denote movement/membership level and the interest areas. We have three groups of constructs that we have coded for. The first two groups were constructed from redefining and contextualizing Wenger's community of practice theory. The third group is emergent from the iterative development of our codebook. The Community Dimensions group contains three constructs that characterize ones' role in the community. These constructs are a measurement of an individual's membership in the community. The second group contains five constructs that refer to the different ways that identity in the community can be constructed (Mechanisms of Identity). These mechanisms demonstrate the dynamic nature of identity formation and how the practices the members engage in can push them in an inward or outward trajectory.

In addition to different trajectories, Wenger describes five different levels of which members of the community can participate and how they move between levels [35, 37-38]; the levels of participation within a CoP are dynamic and can change at any time. In our structuring of the framework, we created subcodes for the Community Dimensions and Mechanisms of Identity that describe the level of membership and dynamic movement within membership levels. The *inbound* subcode describes when the individual is actively looking to move into a more central membership role or increase their involvement with the community. For example, this might mean returning back to the community after a break or trying to become more familiar with the values and goals of the community. The *outbound* subcode describes when the individual has decided to move out of the community or to move to a less-committed position within the community. This could be due to a negative experience within the community or due to graduation. Likewise, the *neutral* subcode is used when the coded segment does not clearly indicate inbound or outbound movement. Two additional subcodes denote moments when the interviewees discuss feeling or acting as if they are on the outskirts of the community (*peripheral*) or core members of the community (*insider*). We chose to only focus on different levels of membership, each representing opposite ends of the spectrum, so that we easily define and identify these membership levels within our data. These static membership level subcodes are used in conjunction with the Community Dimension construct only. Each segment of the interview was labeled with either a Community Dimension or Mechanism of Identity code and will also have a subcode indicating the level of membership currently experienced by the interviewee or the direction of movement within the levels of membership.

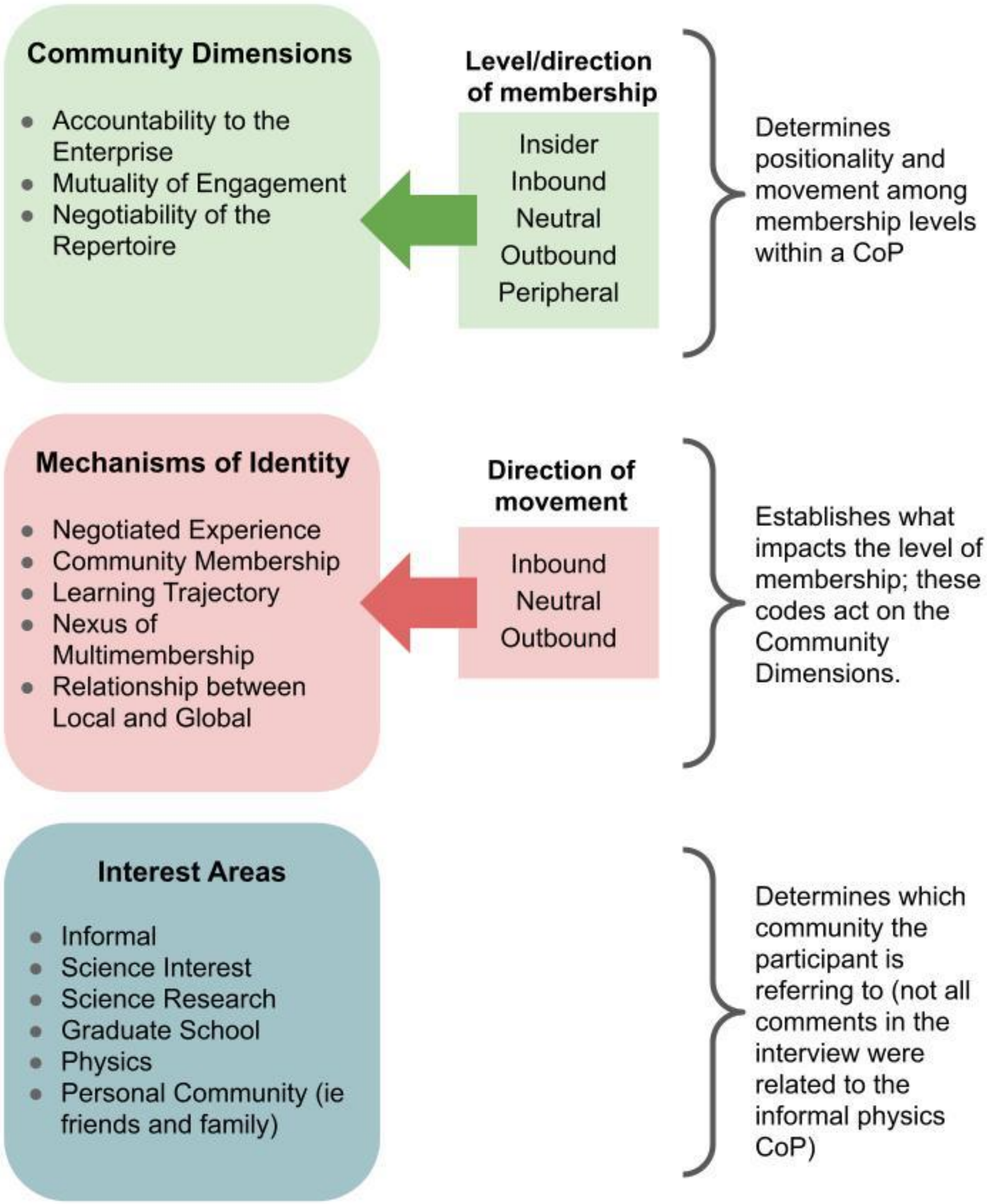


Figure 9: Depiction of three groupings of our operationalized CoP framework consisting of the Community Dimensions, the Mechanisms of Identity, interest areas (or communities) that the interviewees were referring to during the identified segment of the interview.

Finally, in Wenger's theory of CoP there is a discussion about the nature of boundaries and how the community and practices can sit in the intersection of broader social structures. In the process of restructuring the framework, we felt the need to delineate these boundaries by creating a third group that would indicate which particular interest area/community(ies) were being impacted by the engagement of the individual in the practices. While the majority of the interview questions focused on the participants' involvement with their informal physics program, there were times when interviewees brought up their involvement with other communities or interests during their response. We felt it was important to document these parts of their response because it provided insight into how their participation in other groups intersected with their experience in informal programs and physics. During the coding process, the following communities or interests emerged within the interviews: *the corresponding informal program community*, *graduate school*, *personal life* (i.e. family and friends), *physics*, *science interest*, *science research,* and *informal interests* (i.e. involvement in other informal spaces). There was a specific category defined for grad school because the UEs who participated in that category often referred to specific practices and norms of being a graduate student that were not present in the undergraduate students' interviews. These emergent codes are a representation of the interests and communities within our data set and are not representative of all of the possible communities that could have been discussed in the interviews (for example, no participants brought up sports teams that they were a part of).

This complex framework describes how we as individuals become more central members of a community of practice and what factors influence our membership in the communities.

4.5 Community Dimensions

We defined the first group of the framework to determine positionality within the community of practice, i.e. a set of constructs that can help quantify the individual's perception of their membership in the community. Wenger determined that participation in the Community of Practice can be different depending on your level of participation and engagement with the community [38]. Participation can take many forms depending on your involvement and competence - defined by the community as what it values through engagement and participation - within the community and its practices. The Community Dimensions help us determine the degree of membership of the interviewees within a particular community, based on an individual's competence and involvement in each of the dimensions. Table 2 lists these dimensions, provides definitions, and gives examples from both facilitators.

Table 2: Community Dimension construct definitions and examples from the coding.

Community Dimensions	Examples
Accountability to the Enterprise (AE) Describes how members of informal physics programs perceive program goals, the impact of the program, and what is important for them to be a facilitator.	"*The thing that I hope to convey to them is, you know, how they can do it, how good they are basically at doing science*" (Insider)
Mutuality of Engagement (ME) Describes the interactions the interviewee has with other members of the informal physics program. For example, the interactions could be with peers, audience members, or directors/coordinators.	"*Oh yeah, yeah. Sometimes it was really difficult to kind of get them oriented towards writing in their journals or notebooks, and sometimes they just wouldn't listen...*" (Outbound)
Negotiation of the Repertoire (NR) Describes the practices specific to the informal physics program. This includes descriptions of the specific activities or demos that take place during the informal physics program and knowledge that	"*What I've gotten out of it is just being a better teacher, that's for sure, having a better understanding of- but also a better sense of what schools are like these days and what kids are like these days; you know, what it takes to*

facilitators need in order to reach the program's goal.	*get them into science, kind of. I'm generating a sense of that.*" (Inbound)

The first community dimension is known as *Accountability to the Enterprise* and it is related to the understanding, valuing, and working towards the community *domain* by the members of the CoP. Lave and Wenger define Accountability to the Enterprise as a way to consider how members understand the goals/objectives of the community, how they take responsibility and embrace those goals, how they contribute to the achievement of those goals, and their constant negotiation and redefinition of the goals. Because the mission of a community is a joint pursuit, it creates a liability and responsibility among the participants, which in turn defines the practices of the community. This does not mean that all members of the community hold the same ideas or opinions, but that they collectively work towards that higher goal. It is in this constant negotiation and accountability that the community evolves.

The second community dimension, *Mutuality of Engagement*, is related to how the community functions and the forms of interactions between its members. Members of the community participate in activities and efforts that contribute to the community's domain, and the way in which participants engage in those activities is constantly negotiated and redefined. It is the understanding of these actions that defines members and differentiates them from non-members. Within a CoP everyone has their individuality that contributes to the community's engagement and practices; some of the roles and contributions may overlap, and others might be complementary, but all add to the development of the community.

The final community dimension, *Negotiability of the Repertoire,* relates to the competence developed while participating in the CoP. This dimension refers to the understanding, learning, and participating in the practices of the community. It encompasses the set of resources, routines, language, methods of carrying out actions, symbols, and concepts the community has developed through the negotiation of meaning and on working towards the community's goals.

4.6 Mechanisms of Identity

The amount of competence an individual has in a community is related to their community membership, and therefore competence influences identity development. In this study, we are interested in what within the community of practice can foster identity development. Therefore, the second level of our framework is focused on identifying what mechanisms within the informal physics community influence identity changes among the University Educators who are facilitating the program. To determine what influences these changes, the CoP framework identifies a set of factors or mechanisms (five total) that can impact a member's level of participation in the community [35, 38]. Table 3 lists these mechanisms, provides definitions, and gives examples from interviews with both facilitators.

Table 3: Mechanism of Identity construct definitions and examples from the coding.

Mechanisms of Identity	Examples
Negotiated Experiences (NE) Captures how UEs make meaning of experiences that they have through participation in the informal physics program and by interacting with other members.	"*Some days I definitely came away a little frustrated, but you know, that never translated to the interaction with the kids or anything. It was always fun, just maintained a fun atmosphere.*" (Neutral)
Learning Trajectory (LT) Captures what past experiences lead the UEs to participate in the informal physics program and why they might value certain experiences.	*"[I] didn't realize that being a scientist was a thing until I was like sixteen, and I would've loved it somebody came, like you know, when I was eight years old and was like 'hey, look, lasers are cool, you can do this!'"* (Inbound)
Nexus of Multimembership (NM) Captures how the UEs describe being members of two or more communities (i.e. PISEC and physics) in order to understand	*"My only real hesitations weren't related to PISEC necessarily, they were more related to, you know, being able to escape the lab. And that's really just a laboratory politics thing,*

how different memberships contribute to their overall identity.	*that really doesn't have much to do with PISEC.”* (Neutral)
Community Membership (CM) Captures how the UEs are interacting with the practices of the community and how other members of the community might help further competence within those practices.	“*There were a few different tours, and one of them had their teacher with them, their science teacher, and he was really helpful in- it was really informative to me to see how he took what I said and explained it to them. I was trying to make it accessible, but he really knew how to do that, so that was cool*.” (Inbound)
Relationship between Local and Global (RbLG) Captures how UEs are negotiating what their membership in an informal physics program means in the broader context of their lived experiences within this world.	“*I could see a couple of them, definitely. You know, if I were to hazard a guess I'd say that most of them probably won't. But that's kind of the same thing- you know, the people that I took AP physics with like most of them are not in science, like it's just kind of how things go.*” (Neutral)

The first mechanism of identity development is known as *Negotiated Experience*. This construct captures the process of making meaning of experiences through participation in the community, including interactions with other members, and how those experiences form the individual's perceptions of themselves as members of the CoP.

The second mechanism of identity, *Learning Trajectory*, is a construct related to things that have been learned which resulted in the participant becoming a member of the community. This construct incorporates past and possible futures into making meaning of the present; i.e. it captures the experiences that have led facilitators to participate in different ways within the CoP. The learning trajectory of an individual influences which elements of participation are perceived as important and which are marginal. This mechanism helps capture the experiences that give individuals context to determine what things are (or not important) and what has been learned along the trajectory.

The next mechanism of identity, *Nexus of Multimembership,* captures how individuals negotiate being members of different communities. Each individual is composed of multiple identities and negotiating membership to these different communities can impact participation. This construct is meant to capture all forms of participation that contribute to the complete mesh of identities within an individual. In the case of our study, this code captures instances where the UE is describing how participation in PISEC might overlap with other areas of their life such as their physics studies or graduate school experiences.

Community Membership is the fourth mechanism of identity construct and is related to the proficiencies developed and valued by participants in a community. These proficiencies could be skills, capabilities, ways in which community members interact, perspectives and interpretations members share, or the use of a shared repertoire and resources. Community Membership captures how members look at the world, how they relate to others, and their knowledge of how to participate within the community. The more central a member of the community becomes, the more they are perceived as competent by other members and made to feel competent and able to perform well in the practices of the community.

The final mechanism of identity, *Relationship Between Local and Global*, is related to the constant negotiation of the local ways of belonging and how that fits in a broader spectrum of practices and norms. That is, how being a member of a local CoP is connected to being a member of the more universal community. For example, this code would capture the complexities of being part of the physics community at a local institution/department and belonging to the community of physics at large.

4.7 The Coded Narrative

In the following sections we present the stories told by Cecilia and Mike. We focused on the content and language of the stories through the lens of the operationalized CoP framework in order to identify the important experiences that facilitated their identity formation. We use their narratives in the semi-structured interviews to demonstrate how the Community Dimensions and identity mechanisms are present in their stories and how those constructs interact. We identified sections of their stories in which the different elements of the framework and the connection between their participation in PISEC and physics communities is apparent. Through these narratives, we see how the combination of the Community Dimensions and identity mechanisms tell a story about the UEs identity formation. We aim to demonstrate how the operationalized CoP framework can pick up the differences and similarities in Cecilia and Mike's stories. First, we present Cecilia and Mike's positionalities as it pertains to physics in order to help the reader understand the UEs' relationship with their physics identity. Then, we present their narrative in the context of the CoP framework to reflect on experiences, particularly as facilitators of PISEC, that capture the impact on their membership within the PISEC and physics community and the mechanisms that may have facilitated changes.

4.7.1 Cecilia

Cecilia is a third-year graduate student in physics and has always felt as though she was interested in math and used to tinker with things at home, but she was unsure if science was for her because of the experience she had had at school. In eighth grade she was told not to believe in evolution, which she did not like, and she did not enjoy her ninth-grade biology class. However, her attitude changed when she was able to take chemistry, and later, physics. She recalls, “[I] took physics and I was like 'just kidding, I'm going to be a physicist.' And then yeah, it's kind of- I never stopped. I was one of those really lucky kids that went into college knowing exactly what they wanted to study, and I studied it, and then I went into grad school knowing exactly what I wanted to study, and I studied it.”

When asked if she identifies as a physicist, Cecilia says yes, but notes that this has not always been the case. In fact, this was not the case when she started graduate school and dropped out before the first year ended. She mentions that she had some role models and encouragement along the way, including both her AP Chemistry and AP Physics teachers, that were influential in her belief that she could pursue physics. “I would say that those two were, you know, the reason why I'm here. They'll both get invited to my defense.” During the interview, Cecilia also reflected on how others might identify her by saying that those outside of the field most likely see her as a physicist, but her advisors are more likely to see her as a “young physicist [...] budding sort of in the field.” Overall, Cecilia feels confident in her position as a physicist and others view her as a competent member of the physics community.

4.7.2 Mike

Mike is a first-year physics graduate student. He says that his interest in science started early on as a curious kid tinkering around with things, but that it was his parents' support, and in particular his mom's encouragement, that made all the difference. At an early age, Mike's mom taught him how to read, which gave him a lot of confidence to push himself and in his words “put me on a high trajectory.” For example, as a 4th grader doing math in school, Mike wanted to push himself harder. With the support from his teacher, he got to work on some basic algebra problems which reinforced his confidence and ability to do things that seemed harder.

During high school, Mike initially thought he was going to be a biologist because he found his biology teacher very inspiring and he liked the lifestyle that came with being a field biologist. However, his cousin and uncle gave him some interesting books that discussed questions about fundamental science, the universe, and how it works. It was reading these books that made him realize that physics was more the sort of thing he was interested in and he went to college with the idea of pursuing a degree in physics.

Mike thinks that regardless of what triggered his initial interest or what was the catalyst that pushed him to pursue physics as a career, he would have arrived at the same place, physics. He does not doubt his position in physics and his membership within that community. He considers himself a member of the community of science/physics, even explicitly saying “we the science community” at one point during his interview. There seems to be no doubt in his mind that he was meant to pursue physics as a career and that he is perfectly capable of being a physicist. He truly feels as though he belongs in physics, but he also wants others to have similar experiences and confidence, which is what has led him to outreach.

From their statements, both Cecilia and Mike identify themselves as *insider* members of the physics Community of Practice. However, their perception of what constitutes an insider member of that community and their path to get there are different. The factors that have contributed to their perception as core members are also different. In the following sections we will present how the elements of the CoP framework help us distill those differences, as well as indicate in which form facilitating informal physics programs has contributed to their physics membership.

4.8 Community Dimensions of Membership

4.8.1 Cecilia's Story

<u>Accountability to the Enterprise:</u> In her third year as a graduate student, Cecilia felt she could take the time to participate in outreach activities and says, “I thankfully got to the point where I could escape, and my advisor wouldn't kill me.” She believes that outreach is important

and also “looks really good” for those who are aiming to be a professional scientist. However, Cecilia also explains that she has a personal belief about educating others about science. When asked why she participates in PISEC, she says “I've always thought it was important to educate people, especially kids. My reason for that is really that if, you know, I didn't realize that being a scientist was a thing until I was like sixteen, and I would've loved it somebody came, like you know, when I was eight years old and was like 'Hey, look, lasers are cool, you can do this!'” This quote was coded as *Accountability to the Enterprise* for *informal physics* with *inbound* movement because Cecilia is recognizing why she wants to be involved with science outreach and that it would have made a personal impact in her life if someone would have brought science outreach to her. Furthermore, Cecilia participated in some outreach activities prior to PISEC when she was a student abroad and mentioned:

> *When I came back I wanted to get back into [outreach...] So when I finally had the chance and the guts to finally say 'okay I'm going to do this once a week,' you know, that was cool.*

This comment from Cecilia was coded as *Accountability to the Enterprise* with *inbound* movement because she was actively seeking to get involved with the outreach group and explains how she took the step to become a member. We see Cecilia's commitment to PISEC, but also to the outreach community more broadly. When she was not participating in outreach, Cecilia says she missed it and wanted to participate again because she “kind of [has] this obligation to help educate” (*insider* for *informal physics*) and therefore she believes that outreach will be part of her career in some form or another.

In this part of the story, Cecilia describes her motivation and values related to educating others, which align with the PISEC mission. This alignment establishes a path for membership, not only in the PISEC community but also in the physics community. Participation in PISEC, believing in the domain of the community, and wanting to be a member of the outreach community as a whole in order to help others participate in physics has helped Cecilia reshape and reconsider what it means to be a physicist. This theme of reshaping her definition of a physicist is explored more in the other constructs within the CoP framework.

Mutuality of Engagement: Cecilia started to participate in PISEC during her third year of graduate school. In these weekly sessions, she often worked with the same group of 3-4 children engaging in inquiry-based physics activities, such as learning about reflection while playing laser chess. While she did not know what to expect when she first started facilitating in PISEC, she did find the enthusiasm displayed by the children to be a welcome surprise. Throughout her time in PISEC, Cecilia made connections with the children in her group. She mentions that it was fulfilling to encourage the children to follow their passion:

> *Yeah, there was this one kid- just straight up told me I was his favorite in one of these, and it was adorable because the kid's really sharp... So, I would talk to him a little bit. You know, it got a little bit off task, but I talked to him a little bit about math and I told him once that he'd love calculus. I basically told him like whatever happens, just follow what you- because you seem to really enjoy this, follow it and good things will happen for you.*

This interaction was coded as *Mutuality of Engagement* with an *inbound* trajectory for *PISEC* because Cecilia is creating joyful memories with other members in the community. These interactions were impactful to her because she developed bonds with other members of the community, allowing her to move towards a more central membership role. Furthermore, interactions like these helped her develop a sense of belonging in the PISEC community: "It was nice when you kept coming back because [the kids], you know, they know your name and they'd be like 'Hey it's you, work with us!' you know?" (*inbound* for *PISEC*). This recognition by other members in the community helped Cecilia feel valued and like a part of the community and encouraged her to continue participating in the community. These interactions also helped her strengthen her membership in the physics community by reinvigorating her passion for the physics community. For example, when mentioning that she loved giving lab tours to the children because of all of the questions that they tend to ask during the tours, she shares that this allows her to share more about her research. She also has this sentiment reinforced by other members of the community and shares:

> *You know, just kind of one of the girls told me I had the coolest job ever, which again, when you're drudging through grad school is really fun to hear. [laughter] You're like 'oh yeah, I totally do!' (inbound for graduate school).*

These components of Cecilia's story highlight how interactions between members of the PISEC community not only impacted her membership within the PISEC community and the informal/outreach community at large but also her physics identity. Through sharing her knowledge and passion for physics with the children she is able to reaffirm her commitment to the physics community.

<u>Negotiation of the Repertoire</u>: In her story, Cecilia has expressed her understanding and capabilities related to the practices of the physics community and how competence and confidence within those practices are key to becoming a more central member. She even describes how throughout her path to become a physicist, she did not think she belonged in the physics community because she was not good in the practices . For example, when asked if she felt like she belonged in physics she replied "No, especially when I started grad school or when things got

really, really hard or I was struggling with an experiment or something, like clearly I just don't belong here." This instance of examining her identity as a physicist was coded as *outbound Negotiability to the Repertoire* for the reason that she is struggling with her sense of belonging because of feeling inadequate while engaging in the practices of the *physics community*. However, she goes on to say "and then of course I got the experiment working and it was kind of like what? That felt nice." , which was coded *inbound Negotiability to the Repertoire* because at the point when she regained confidence in her ability to engage in the practices, her sense of belonging was reaffirmed.

Through her participation in PISEC, Cecilia has become more aware of the different kinds of people that can be considered members of the physics community. She believes that programs like PISEC can help everyone understand that physics is awesome and can be fun, even if they do not pursue it as a career. In a way, participating in PISEC has broadened her perception of the repertoire and practices that determine your membership within the physics community. When she is asked about what was the most important thing she has gained from participation in PISEC, Cecilia says:

> *And so, I'd say kind of the best thing that I've taken away is an appreciation for kind of the spectrum of people, and that not everybody has to be a scientist to appreciate science. And, I think that's something that I really like" (Negotiation of the Repertoire on an inbound trajectory in PISEC and the physics community).*

Finally, engaging in the practices of PISEC has given Cecilia the opportunity to share her membership in the physics community by normalizing this pathway and inviting children to participate in it. She recalls her interactions with the youth participants in PISEC by saying, "But you know, as a whole you could kind of build a rapport and in a sense be like 'I'm a normal human being, kind of nerdy, but normal. And you can too.'" Cecilia's ideas about building up a rapport with the students has been coded as *Negotiation of the Repertoire* for an *insider* member of *PISEC* because she is commenting on her experience with the sort of actions that are possible during participation in PISEC and her ability to impact youth.

For Cecilia, her membership in PISEC is deeply connected to her membership in the physics community because she believes that outreach is a really important part of being a physicist. This connection is mainly due to her belief in the importance of educating others, especially children, about science so that they can see science as a valid career option. Furthermore, she also believes strongly in instilling in children the confidence necessary to enjoy science, even if they do not pursue science as a career. Engaging in the practices of PISEC gave Cecilia the opportunity to share her interests and passion from the physics community to others who may not yet be part of that community. This sharing of passion and interest potentially help strengthen her membership in the physics community.

4.8.2 Mike's Story

Accountability to the Enterprise: As a graduate student, Mike started to get involved with some outreach activities because he wanted to help to get people into science. He says:

> *[PISEC] just seemed like the most applicable outreach opportunity. I loved the fact that it was going to schools and doing physics. Yeah, I think it was really the main one that I saw in science for outreach.*

Mike was actively looking to engage in some informal activities when he found PISEC (*Accountability to the Enterprise, Inbound*). The fact that he was actively looking for outreach and that he identified PISEC as the best option indicates a level of commitment to the informal community and to the PISEC community in particular. However, Mike's statement about searching for an opportunity that would allow him to go to schools and discuss physics also indicates a level of accountability to the physics community because he was excited about the physics aspect of PISEC. Part of Mike's goals for getting involved in informal physics was to get people into science and he identified the PISEC domain as being aligned with his vision.

Furthermore, Mike expressed that his desire to get involved with the PISEC community was connected to his professional growth. As he grew as a physicist, Mike felt the need to help others pursue science and become engaged with science, indicating a strong commitment to the science and physics community in particular. Mike shares this vision when he said, “[K]ind of the more I've grown as a scientist, the more I've wanted to help others get into science.” This statement was coded as *insider Accountability to the Enterprise* within *informal physics* because Mike is talking about how he has consistently grown to be aligned with that domain. The most important goal as a member of PISEC, for Mike, is to encourage children to believe that they can do science. He sees his own experiences reflected in the goal of PISEC because he knows that an external push is what got him to pursue physics. The mission of PISEC, as he sees it, aligns with his own values and is a reason for his commitment to the PISEC community.

<u>Mutuality of Engagement</u>: Relationships and connections with other members are very important for Mike to engage in at community and is especially true for the PISEC community. When looking for outreach opportunities, something that contributed to Mike's decision was the way the group was structured. He recalls that “everyone was really well organized, and I felt like the kids got a lot out of it. A good group of people.” This was coded as *Mutuality of Engagement* on an *inbound* trajectory for *PISEC* because Mike is explaining how his interactions with other members have been positive and fulfilling. Furthermore, Mike often mentioned that the connections made in PISEC were one of the main things he gained from participating in the

program. Mike describes the interactions with his PISEC peers as “cathartic” and as “a good break from the lab work.” The time spent and interaction with just the other UEs in PISEC were seen by him as stress relievers:

> *I mean the car trips are always just fun, just shooting the s[], and then when you're there you're doing fun activities. I usually forgot about whatever thing I was stressed about by the time I was done, which was nice.*

This recollection of interactions with other facilitators was coded as *inbound Mutuality of Engagement* for *PISEC* because Mike is really honing in on how he enjoys spending time with others involved in PISEC.

Along with talking about his fellow facilitators, Mike also extensively discusses the deep connections he made with children in the program, which in some cases were so important that he referred to them as a “brotherly connection.” These connections are also reflected in his comments about seeing the children engage with the activities, particularly when they came to his lab and he had the opportunity to share his research:

> *One of those kids just straight up told me I was his favorite in one of these, and it was adorable because he's just, the kid's really sharp... He was my favorite. It was nice when you kept coming back because they, you know, they know your name and they'd be like 'hey it's you, work with us!' you know?*

This quote from Mike's interview was coded as *inbound Mutuality of Engagement* for *PISEC* because Mike is happy to make connections with the students and refers to these experiences as being “cute” and “fun”. Through his interactions with these two boys, Mike is able to feel valued by Pedro and Luis as a PISEC community member.

Mike's involvement with PISEC was furthered by the relationships that he built both with his peers (other physics students) and with the youth who were members of the PISEC community. Not only did these relationships seem to increase his enjoyment of PISEC, but they also created a path for membership and allowed Mike to move inward toward a more central membership role. These connections took place on the way to the schools, during the activities at the schools, and even outside of the school setting (back at Mike's lab where he led a tour for the students) which allowed for his membership in PISEC to overlap with his membership in the physics community.

Negotiation of the Repertoire: By building relationships with the different members of the PISEC community, Mike learned new skills and practices of PISEC. For instance, he says:

> *I guess it seemed to me like the older brother who was maybe a little more, you know, attentive and observant, just kind of more of an observer, he would do well because of that, in science, and I think he would enjoy it. But the younger brother was also very, very skilled- like, he tended to be the one who would jump in and do something first. So, I think both of them would make good scientists. I think based on the personalities maybe it seems more likely that the older brother would go into science and the younger brother would just choose to do something else.*

This reflection about some of the students Mike worked with was coded as *Negotiation of the Repertoire* for an *insider* member of the *physics community* because Mike is recognizing the strengths that allow one to succeed within physics (or science more broadly) within the two students. These interactions with the students impact his integration and therefore membership in the PISEC community, as well as his desire to continue participating in the PISEC because he sees these interactions as being in line with his personal desires to help others pursue science (as seen in his Accountability to the Enterprise examples).

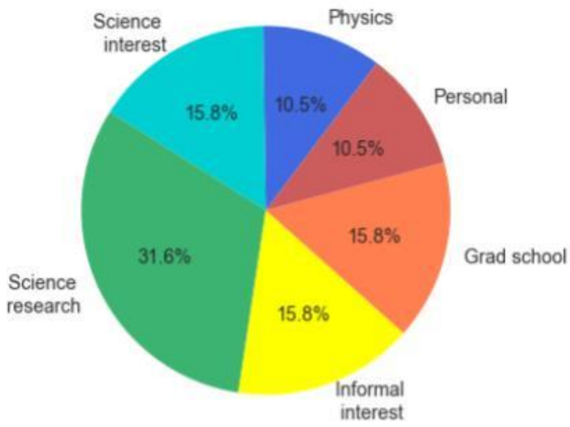
For Mike, the intersection of physics and PISEC takes place when both communities provide him with opportunities to engage in activities that align with his values and goal -- engage more people in physics-- while sharing his passion for physics. The PISEC community is providing Mike a space to engage with practices that are important to him and to his ideas of being a physicist. But all of these practices have been, in some form or another, supported/fostered by the relationships he has formed with members of the communities or while engaging with the domain of the community.

4.8.3 Intersecting Interests Codes

When we started coding the interviews with the CoP framework there was a need to specify what community the subjects were referring to. In some cases, while the experience happened in a specific community, the participants expressed that the experience also affected their membership in another community or area of interest. For example, when Cecilia discusses her hesitations for participating in PISEC, she says that her hesitations were not related to PISEC itself, but that time spent in PISEC was time not spent in her research lab. In Figure 10, we show the intersection between PISEC and other interests that were present in both Cecilia and Mike's interviews. The overlap between the areas of interest are represented in terms of the total amount of overlap that we saw with PISEC. While we are representing the overlap between two areas of interest, it was possible for more than two interests to overlap.

Through the comparisons seen in Figure 10, we notice that there is no particular community that Cecilia or Mike perceive as having more connections with PISEC; instead it seems as though participation in all these interests is balanced. Both seem to understand how the different interests and communities can intersect, allowing them to express their identity and therefore membership between their different interests and memberships without hindering participation in other communities or areas of interest. In fact, participation in PISEC and the physics community compliments their values and motivation for participation in all of their interests. This confirms what we observed in the Community Dimensions, in which their *Accountability to the Enterprise* is connected to their passion for physics.

In particular for Cecilia, her connection with the other members of PISEC sparked motivation not only within her physics research but also with her belief that continued participation in PISEC was actually having an impact on the children and allowing her to feel like she was doing something significant. Cecilia's balance across the intersection of the interests can be linked to her path into physics and informal. During the interview, there are different occasions where she expresses that participating in informal physics is important because it allows her to provide those experiences to others that she did not have as a child, which - she believes - could have had a positive impact on her path to becoming a physicist. Cecilia also found that participating in informal programs became a source or motivation throughout her struggles in graduate school. Mike's case is driven by his desire to inspire others to feel the same passion he feels for physics.



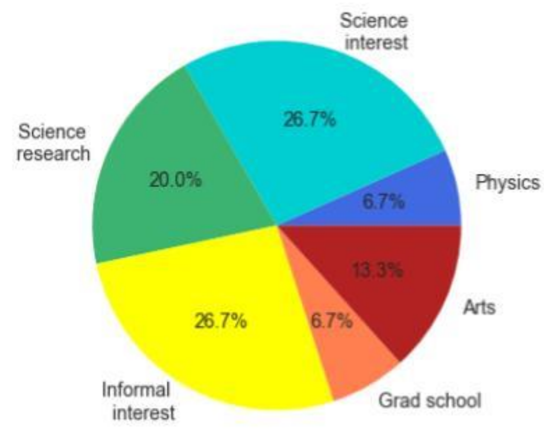


Figure 10: Percentage of overlap between PISEC and other communities (out of total percentage of overlapping areas for PISEC) for Cecilia (left) and Mike (right).

4.8.4 Summary of Community Membership

For both Mike and Cecilia, their membership to PISEC, and the informal community more broadly, is linked to their physics identity. As physicists, they both believe, to varying degrees, that it is important to engage with the public to show them that physics can be awesome and accessible and that anyone can pursue their interest in physics. Therefore, we see the PISEC domain aligning with their personal values and establishing a clear path to membership. Furthermore, participation in PISEC also supports their physics identity by allowing them, as members of the physics community, to share their passion for the field (connected to their *Accountability to the Enterprise* in physics), demonstrate their knowledge of the content and practices of the field (*Negotiation of the Repertoire*), and engage with the children in physics practices (*Mutuality of Engagement*).

In Figure 11, we present the percentage of Community Dimensions for the PISEC community seen within Mike's and Cecilia's interviews. The codes have been separated into the subcode categories - Insider (dots), Inbound (circles), Neutral, Outbound (diagonal), and Peripheral (closely spaced diagonal) - to show the percentage of codes that were coded as movement or community membership levels. Mutuality of engagement did not produce any peripheral or insider codes and Negotiation of the Repertoire did not produce any outbound or peripheral codes. The counts are normalized to the total number of codes in each interview, so that the total number of codes in each interview is treated as 100%. We chose to present the distribution of Community Dimensions for only the PISEC community in order to paint a clearer picture of how their informal experience impacted other areas of interest. It is important to state that the length of the interview did not necessarily imply a higher number of codes overall (Mike's codes per minute = 4.64 and Cecilia's codes per minute = 6.22).

In Figure 11, we are able to visually appreciate the differences in experience Mike and Cecilia had and how those are reflected through the Community Dimensions. From Cecilia's Community Dimensions, we can infer that she perceives herself as an inbound member of the PISEC community. She has a very good understanding of the domain of the community and continually contributes to this domain, which can be seen through her *Accountability to the Enterprise* (AE). However, she seems to still be developing the community (*Mutuality of Engagement;* ME) and practice (*Negotiation of the Repertoire;* NR) dimensions. While Cecilia has definitely engaged in interactions with other members of the community, mostly the children that participate in the program (ME) as they work together on activities, and she has learned about the activities in PISEC (NR), there are fewer number of codes in those dimensions, possibly due to the fact that she has only participated in PISEC for one semester at the time of the interview and had to missed a couple of weeks during the semester. Similarly, from Mike's distribution, we can infer that he mostly identifies as an inbound member of the PISEC community. He has a very good grasp of the *Accountability to the Enterprise* dimension, which can be demonstrated by frequency of codes . However, similar to Cecilia, Mike is still working on developing the practices and connections with other members of the community in order to become more a central member of the PISEC community.

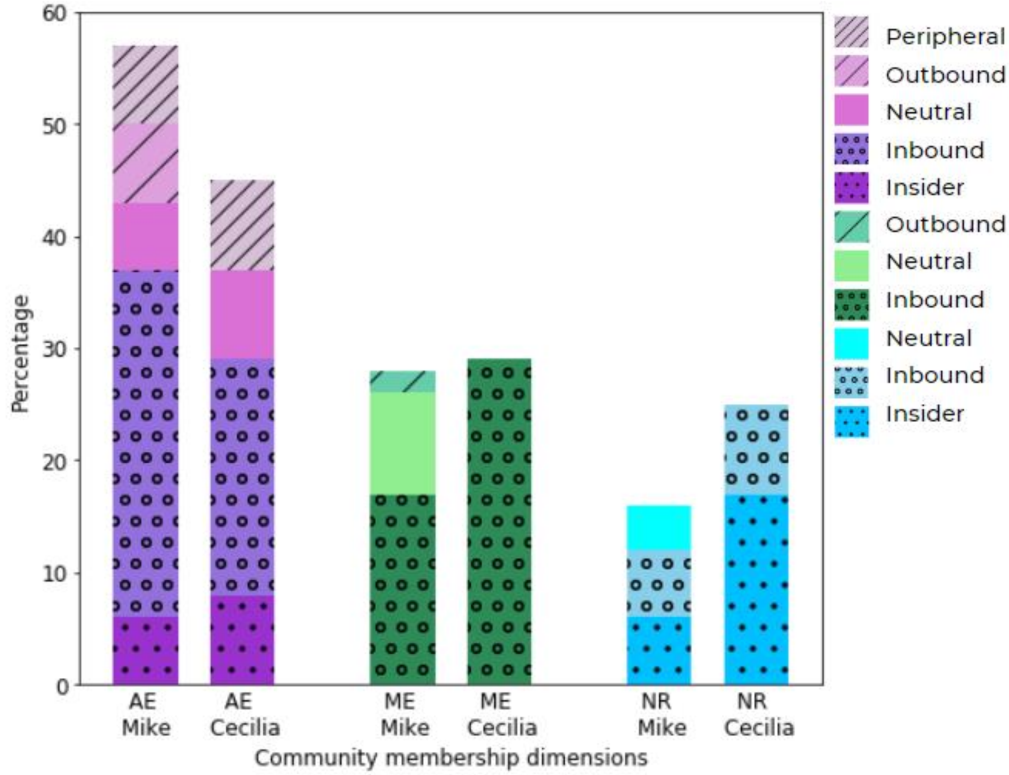


Figure 11: Community Dimensions within PISEC represented as a percentage of all community membership codes for both Mike and Cecilia.

From the comparison of these two cases, which only represents a snapshot of Cecilia and Mike's path towards membership within the PISEC and the physics community, we notice that membership development is not a straight path but rather a gradual process. Developing membership, and therefore identity is dynamic. We can move in and out of the community at different points of our membership - becoming more central members or retrieving to peripheral - depending on how we align with the community's dimensions and the experiences we have as members. At the moment of the interviews, both Mike and Cecilia had opened a path to become central members of the PISEC community.

4.9 Mechanisms of Identity

Through the Community Dimensions we were able to characterize Mike's and Cecilia's membership within the PISEC CoP. We noticed how membership shifts and changes based on how the Community Dimensions are encouraged/supported (or not) through their experiences in the program. These movements within levels of membership are often prompted by different mechanisms that impact the community membership dimensions. In this section, we show how the operationalized framework is able to capture what identity mechanisms have contributed to Cecilia and Mike's membership within the PISEC and physics community. In Figure 12, we present the percentage of Mike and Cecilia's identity mechanisms that were connected to their participation in the PISEC community. As with the Community Dimensions, the counts are normalized to the total number of codes present in the individual interviews and then we calculate how much of that represents each of the mechanisms. Here we will discuss the mechanism and what it meant for Cecilia and Mike during their participation in PISEC.

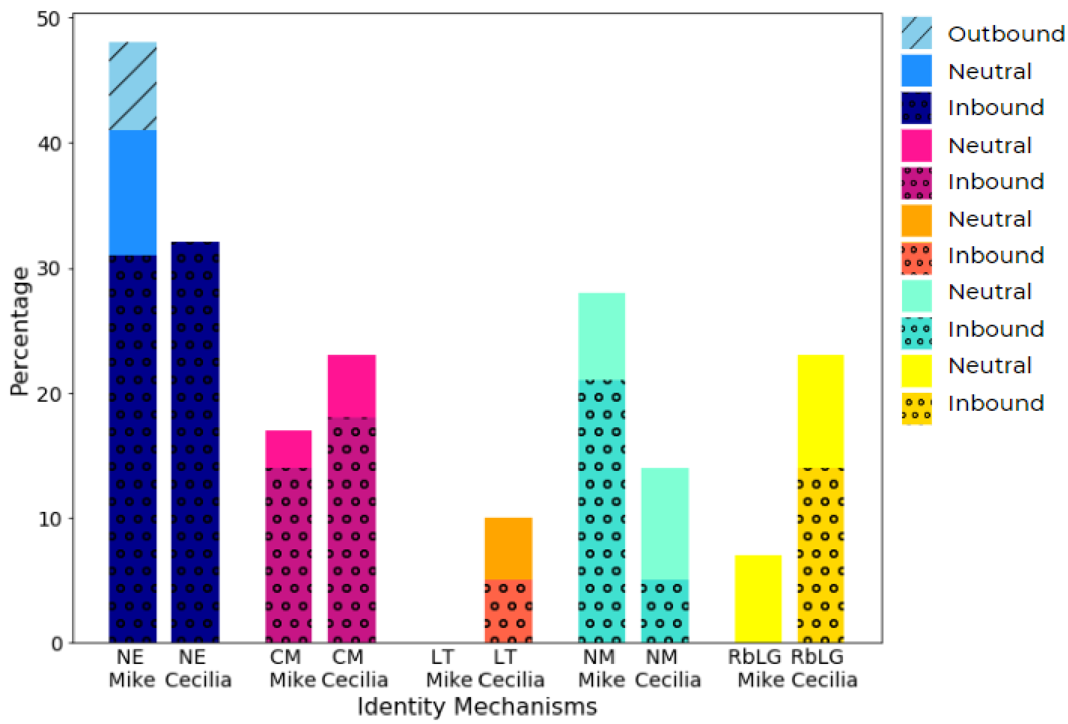


Figure 12: Identity mechanisms for PISEC shown as a percentage of all identity mechanism codes for both Mike and Cecilia. The codes have been separated into the subcode categories - Inbound (circle), Neutral, and Outbound (diagonal lines) - to show movement.

4.9.1 Mike's Story

Negotiated Experiences: Through Mike's story, and the codes reflected in Figure 12, we can see that the most influential mechanism for Mike's movement within the PISEC community is from interactions with members of the community and how these interactions bring meaning to his participation. Mike's *negotiated experiences* with others in the PISEC community of practice give him a sense of belonging in the community and recognition as a member. These experiences show how the interactions with the other members, particularly the children, reaffirm Mike's motivation to contribute to the PISEC community. He says:

> *I think really it just came down to the fact that they [the children] were getting involved in [the activities], like they were participating, you know? That right there is the statement I really looked for. I don't know if any of them are more*

likely to become scientists, but you kind of imagine so; or at least more likely to think that it's a possibility. Whether they'll actually want to do that or not, you know, at that point in their life.

This quote was coded as *Negotiated Experiences* for an *inbound* trajectory in the *PISEC* community because Mike is talking about the positive interactions with the children and that he believes they want to become scientists. Mike's motivation for participation in the PISEC community is also linked to his participation in the physics community. When Mike was asked about his favorite moment while participating in PISEC, Mike recalls, "That was when Pedro asked if he could work in the lab, so that was my favorite" (*inbound Negotiated Experiences* for *PISEC*). Both of these quotes reflect how Mike's membership in PISEC allows him to engage more people in physics while simultaneously sharing his passion for physics. By having positive interactions with the children, and seeing them truly engage and enjoy the activities, his membership within the PISEC and physics communities are reaffirmed. Furthermore, Mike mentions that he has formed brotherly connections to some of the children in the program, which indicates a strong sense of belonging to the community. While this connection was during that particular semester, it could still be a motivation for continuous participation because he is wanting to create more connections. Mike also mentions that interactions with his peers - physics graduate students that facilitated PISEC activities - were positive, always fun and stress relievers. These interactions may have also contributed to his sense of belonging in both communities.

Community Membership: Beyond those connections, Mike also reflects on the forms of competence and skills he learned through his participation in PISEC:

I think I definitely have learned a lot. And this is something I wanted to get out of [PISEC] too; I knew I would learn a lot about what it takes to teach, especially *young kids, science, and expose them to ideas. I think I definitely developed- What I've gotten out of it is just being a better teacher, that's for sure, having a better understanding of- but also a better sense of what schools are like these days and what kids are like these days; you know, what it takes to get them into science.*

Mike's reflection was coded as *Community Membership-inbound* for *PISEC*, because he is talking about the teaching capabilities that he developed as a member of PISEC. Mike's reflection on how to teach the youth about science and to co-think about experiments with them shows that these experiences were an essential mechanism in terms of him becoming a central member of PISEC. Furthermore, Mike comments on interactions that he experienced with the classroom's teachers while in PISEC, "[H]e (the science teacher) was really helpful in- it was really informative to me to see how he took what I said and explained it to them. I was trying to make it accessible, but he really knew how to do that, so that was cool." When Mike was talking about how the science teacher explained things to the students, he was sharing how another member of the PISEC community helped him learn how to be a better member in PISEC, therefore coded as *Community Membership-inbound* for *PISEC*. These instances indicate that Mike felt he was growing as a member of the PISEC community and moving towards a central member by understanding and learning the practices of the community through interactions. This sense of growth and competence are important factors for continuous participation in a community of practice and for building identity.

Nexus of Multimembership: The most important role as a member of PISEC for Mike is to convey to children the confidence or push they need to believe that they can do science. He reflects on how an external push helped him pursue physics as a career. Therefore, he is now providing that push to the youth in PISEC:

> *To get more people into science- because I think certainly that's obviously the goal of PISEC, or at least to encourage kids and show them that they can do it if they wanted. And that's a big thing, is motivation and self-esteem stuff.*

This reflection from Mike was coded as *neutral Nexus of Multimembership* for *PISEC* and *science interest* because it is showing how Mike connects the goal of PISEC and with being interested in science, although he is not speaking about this in a positive or negative sort of way. This goal of PISEC aligns with Mike's own values and is possibly a reason for his commitment to the program. His constant negotiation for participation between physics and PISEC appears to have an impact on Mike's membership movement within PISEC, which was reflected in the community dimension of *Accountability to the Enterprise*.

Mike's personal goals and mission aligned with PISEC domain, which is intertwined with his participation in physics; as he becomes a more central member in the physics CoP, it is important to him to share his passion for physics, engage people in physics, and help them build the confidence necessary to pursue a career in science. Being involved in PISEC has allowed Mike to do all of those things that are important in the physics community. He comments, "But yeah, kind of the more I've grown as a scientist, the more I've wanted to help others get into science." This reflection about wanting to share his experiences in science with others was coded as *Nexus of Multimembership* with an *inbound* trajectory for both *informal physics* and *science research* because Mike is explaining how his growth as a scientist influences his growth in the informal community. This connection permeates his interview as he discusses his constant negotiation between physics and PISEC. However, while Mike believes that graduate school was a good time to start doing more outreach, he is also often conflicted between sharing his time between graduate school and outreach programs. He expresses this by saying:

Yeah. I wouldn't've started [PISEC] if I were partway into the first semester, you know, and I knew how intense it would be [referring to the semester]. But yeah, [PISEC] is not a big time commitment [...] And even when the concept of going [to PISEC] was stressful, going itself was very cathartic and nice. It was always fun, as it was this semester. It was always just a stress reliever" (neutral Nexus of Multimembership for both graduate school and PISEC).

Overall, Mike's experience reflects that his growth as a member of the physics community leads to a membership in PISEC and informal physics community more broadly, in order to achieve his goal of spreading a passion for science and physics. In a similar way, the more he participates and becomes a more central member of the PISEC community his membership in the physics community gets reaffirmed. Therefore, the Nexus of Multimembership between the physics and PISEC communities for Mike can be seen as a mutualistic relationship in which his participation in one strengthens his participation in the other and vice versa.

4.9.2 Cecilia's Story

Unlike Mike, whose code frequency was more heavily concentrated on some of the identity mechanisms, Cecilia's movement in PISEC seems to be driven by all the identity mechanisms. In Figure 12, we see that Cecilia's experiences are represented throughout all five of the mechanisms.

<u>Negotiated Experiences:</u> Similar to Mike, Cecilia's connections with the children in the program seemed to have an impact on her membership. For Cecilia, the interaction with the children helped reaffirm her motivation for participation in PISEC; seeing the children positively respond to engaging with the physics activities made her feel as though the goal was being accomplished. When asked about her interactions with the students, she comments, "I was surprised at how enthusiastic all the kids were, and that was something that definitely took me by

surprise. I guess it's because it's a voluntary thing." This quote in Cecilia's interview was coded as *inbound Negotiated Experiences* for the *PISEC* community because she is excited by her interactions with the children. The enthusiasm displayed by the youth participants gave Cecilia a sense of belonging because she was recognized and able to build up a rapport with them. She shares this when she comments on how the children recognized her over time as she kept coming back to the schools and one student even told her that was their favorite.

However, these experiences also impact Cecilia's membership within the physics community. She is not only able to share her passion for physics and receive positive responses from the children, but the children also encouraged her continuous participation in the physics community. There was an instance (detailed in Cecilia's Mutuality of Engagement section) where one of the students participating in PISEC commented on Cecilia having "the coolest job ever" (which was also coded as an *inbound Negotiated Experience* for *graduate school*). This reaction to being a graduate student was something that encouraged Cecilia to take that viewpoint about her job, even when the going is tough.

In addition to talking about how she was able to interact with the youth in the classroom space during PISEC, Cecilia mentions experiences where the youth come into her space within the physics community. As part of PISEC, the students are able to go on lab tours at the university and Cecilia was able to show her lab and research to the PISEC children:

> *So it's really cool, and that's always one of my favorite parts is showing the kids around the lab. I just, I love that because they ask all these questions and I just eat it up. So I don't know, it's been really neat for kids to be like 'wow, that's really cool!' It made me feel like I'm actually doing something.*

This remark about the lab tours was coded as *Negotiated Experience-inbound* for both *PISEC* and *science research* because Cecilia loved interacting with the children about her own work. These experiences, both during the time spent in classrooms after school and in the labs on campus, allowed for Cecilia to move toward a more central membership role within PISEC and the physics community because she is able to have positive experiences with the children that allow her to appreciate her role in both communities.

Learning Trajectory: Cecilia's childhood experiences (or lack of) with informal programs seems to be a driving force for her continuous participation in PISEC and informal programs more broadly. She shares that when looking back, she wishes there had been more access to opportunities that would allow her to engage with science and physics sooner. We can see this lack of experience impacting how Cecilia views outreach now when she comments on how she wishes someone had introduced her to science at a younger age and now she believes it is very important to educate others (see Cecilia's Accountability to the Enterprise section for the quote). This instance of Cecilia recognizing the importance of educating youth was also coded as an *inbound Learning Trajectory* for both *informal physics* and *science interest* because she is relating her past and present experiences to her involvement in both science and PISEC.

However, Cecilia also takes the opportunity to reflect on ways that she was encouraged to pursue STEM as an option. She believes that part of her continuation in participating in physics has been because of positive role models and figures throughout her career that have instilled her with confidence and the idea that she is capable of doing physics. She shares how influential some teachers have been when she says, “My high school chemistry and my high school physics teacher, I had them both actually again my senior year because I took the AP level of both of those, and they were just like yes, you can do this, this is a thing that you can do for the rest of your life. And that was just, it had never even dawned on me" (*inbound Learning Trajectory* for *physics* and *science interest*). She knows that these experiences were impactful in her own trajectory through science and so she speaks about offering similar experiences to the student participants in PISEC.

Furthermore, outreach became an important part of her participation in the physics community and that positive experience lead her to seek other similar opportunities:

> *[I] was actually a grad student for like a month and a half in [abroad physics institution]... Short story long, I ended up dropping out, but for that month and a half, couple of months that I was there, outreach was really big... There were multiple times that I went to the university and helped with outreach for kids or, you know, went to like a mall in the city and helped with outreach for kids… when I came back to [U.S university] I wanted to get back into that in some situation. So, when I finally had the chance and the guts to finally say okay, I'm going to do this once a week.*

In this quote Cecilia is expressing how past experiences have been key to determine her participation in the different communities and thus it was coded as *Learning Trajectory* (*outbound* for *grad school* and *inbound* for *informal physics*). Her negative experience in the abroad physics institution where she did a semester had a positive side, which was participation in informal physics activities. She then pursued more of those positive experiences with informal physics. Therefore, experiences categorized under *Learning Trajectory* were a very important mechanism for Cecilia's participation in both the PISEC and the physics community because much of her past and present revolved around being interested in science and being interested in informal/outreach opportunities.

Community Membership: For Cecilia, engaging in the practices of PISEC helped her gain new perspectives and ways of looking at the world. When asked what she has gained from PISEC, she comments on how she has gained an appreciation for the spectrum of people who can participate in physics, and science in general (see Negotiation of the Repertoire section for Cecilia's quote). This instance in her interview was also coded as a *Community Membership* on an *inbound* trajectory for *PISEC* and *science interest* because Cecilia is relating her experiences in PISEC with her views on science as a community. Furthermore, participation within the PISEC community also strengthens her connection with the practices of the physics community because the children recognize her as an expert of the physics domain. This recognition allows Cecilia to feel more competent in the physics practices and she shares this when reflecting on what she has gained from PISEC: "the biggest benefit that I've gotten is, you know, I don't want to say the ego boost, but kind of you know having kids come up to you and be like 'wow, this is really cool!" (*inbound Community Membership* for *PISEC*). By being a member of the PISEC community, Cecilia is not only learning new skills, practices, and norms of interactions, but through the connections with members of the PISEC community she is also gaining appreciation for her membership in the physics community.

Nexus of Multimembership: As with Mike, Cecilia's negotiation of participation in the physics community and PISEC has had an impact on her membership within both communities. She also has struggled to manage the time spent on both communities, but she was more driven by pressure from the physics community to not engage in activities outside her own research. She shares this as a reason for questioning if she should get involved with PISEC when she says:

> *My only real hesitations weren't related to PISEC necessarily, they were more related to, you know, being able to escape the lab. And that's really just a laboratory*

politics thing, that really doesn't have much to do with PISEC [...] You know, the time lost in the lab I could always make up later. And it was really just, it was just fun. Like I might do a semester off semester on sort of thing, but really that would be more to give other people a chance to experience it. I enjoyed PISEC and I hope it continues.

This sense of hesitation and her reasoning for being involved with PISEC was coded as a neutral *Nexus of Multimembership* experience for both *PISEC* and *science research* because Cecilia is talking about how PISEC and her lab work are at odds with each other. In Cecilia's case, membership in the PISEC community seems to clash with her membership in the physics community mainly due to recognition by members of the physics community and the lack of support that she receives from others in her research lab. However, she sees outreach as an important element of being a scientist and plans to continue on it throughout her career path. This is clear when asked whether she can see herself participating in physics without doing outreach and she responds by saying:

It would be kind of lame. I mean I could, and I did for the first four years I was in grad school, or the first three years I was in grad school. But I always missed it when I wasn't a part of it. You know, I don't think it's essential for me, you know, to get research done [...] but I kind of have this obligation to help educate that I've felt (inbound Nexus of Multimembership for physics and informal physics).

Through these thoughts from Cecilia, we can see that she struggles with being involved with both outreach and physics, but she persists because the goal of outreach is personally very important to her.

<u>Relationship between Local and Global</u>: Cecilia feels a deep obligation to educate people

and engage them with science, and physics in particular. This obligation is driven by her sense of belonging to the physics community and wanting to contribute to engaging more people in that community. She has expressed her sense of obligation in different forms throughout her participation in the PISEC community and how her participation in that community connects to a bigger purpose. She shares:

> *You know, it was more kind of like how can I help people, you know. You hear about people like, you know, I developed an organization that builds, you know, bathrooms in Africa for underprivileged people that don't have bathrooms, and I'm like wow, that's cool. But I'm just, I'm not built that way. Kind of the way that I've always thought that I could make the most impact in this world is to try to advance science knowledge, and so that's kind of at the end of the day what gets me through. The shorter answer though is that it's awesome.*

This reflection on how Cecilia's participation in PISEC can be related to the world more broadly, was coded as *Relationship between Local and Global-inbound* for both *PISEC* and the *physics community*. Cecilia is recognizing that her strength in this world is related to telling others about science. She sees the connection between participating in PISEC, the local impact (getting the group of children that participate more interested in physics/science) and how that translates to a bigger picture (changing society's awareness of physics/science). Cecilia's perception of how the local impact connects to a larger picture becomes a big driver for her membership in the PISEC community, the outreach community, and the physics community more broadly. This connection can be seen when she shares her thoughts on who gets to do science and why the broader community should be involved:

And so maybe in a sense that's what I get out of it, is that when people say science is awesome and we should pursue it, they eventually go vote and, you know, the NSF gets a bunch of money and I get to take some of that money and go do science with it in that sense. But it's kind of a more long-term thing. Like I just want people to, I want everybody to understand that like science isn't out to get you, it's not going to, you know, attack your belief system unless you let it. You know, it's here to kind of save us from ourselves in a sense (inbound Relationship between Local and Global).

Overall, Cecilia shares a variety of experiences and views that impact how she participates within PISEC and the physics community. These experiences are both from her past (experiences from her childhood) and through her present participation in both communities. During the interview, Cecilia shares how interacting with other members of the PISEC community and how experiences within PISEC have impacted her own perception of her membership within physics. She also shares how these experiences and interactions engage with her previous trajectories and her worldview.

4.9.3 Summary of Mechanism Constructs

In this section, we examined what mechanisms of identity within the operationalized CoP framework impacted Mike and Cecilia's membership in the PISEC community. Additionally, we examined how these mechanisms linked participation in PISEC with participation in the physics community. As noted in the community dimensions section, Mike and Cecilia's membership within PISEC is connected to their value of engaging with the public, particularly children, in order to show audiences that physics can be awesome and anyone can pursue it. Therefore, we expected to find that the mechanisms that had a larger impact on their membership were related to how their participation supported their goal of engaging more children in physics.

In Figure 12, we notice that for both Mike and Cecilia, their relationships with other members (*Negotiated Experiences*) are the most important mechanism within the PISEC Community of Practice to move them towards building identity. This is in agreement with other frameworks that have studied identity and sense of belonging, in which being recognized by others in the field was essential to form identity [1-2,57,77].

In Mike's interview, we can see that *Negotiated Experiences* (about 50% of his overall mechanism codes, seen in Figure 12) was appreciated through his comments about the brotherly connection developed with some of the children in the program and, more specifically, that these interactions allowed him to achieve his goal of seeing children positively interact with physics. He shares that the youth participants even hinted at working with him in the lab when they grow up or become scientists. The second most relevant mechanism present in Mike's path to membership is the *Nexus of Multimembership* mechanism (in figure 4, we see that this is about 30% of all of the mechanism codes). In this case, it is Mike's strong sense of belonging within the physics community and his desire to share that with the children so they can also pursue a career in science that inspires him to continue participating in PISEC. This desire to share his physics experiences with the youth participants was especially true after experiencing positive interactions with the children during PISEC. Finally, the third relevant mechanism that appeared in Mike's coding was connected to how his participation in PISEC allowed him to learn more about communicating and engaging the children in science (*Community Membership).*

For Cecilia, we observed that all the mechanisms of the framework contributed in some form or another to her membership in the PISEC community (in fact, we only saw Learning

Trajectory in Cecilia's interview). Like Mike, the connection and interactions with the children in PISEC and their positive responses to engaging in physics activity was definitely the most significant factor that influenced her membership. Her main driver for participating in the PISEC community is her personal obligation to educate others, children in particular, about how exciting physics is and the purpose of physics. In her case she seems to perceive that all the mechanisms contribute to achieving her goal.

Finally, it is interesting to note that even though the structures of the program and the degree of participation for Mike and Cecilia are similar (going to the school once a week to facilitate some activities), their experiences were different enough that Cecilia perceived support of all the identity mechanisms, while Mike only discussed a subset of the mechanisms. For future work, we are interested in studying whether support from all the mechanisms is important or even necessary for becoming a central member of the community or if individuals can become central members by only experiencing some of the mechanisms.

4.10 Alternative Experiences

In this chapter, I have discussed in detail the two examples of Mike and Cecilia's experiences as PISEC facilitators. However, in the beginning I also mentioned that we started the operationalization process with other data. First, we looked at the Community Dimensions within a set of interviews from a single facilitator in Science Theatre. We also started with the Mechanisms of Identity constructs by looking at interviews from Sorcha and Eoin, two other PISEC facilitators. The personal experiences of each of these facilitators were both similar and different from what we saw with Mike and Cecilia and offer a different perspective on the codes. I am going to show snippets of their experiences here in order to discuss alternative views and discrepant data in this study. I am using the term “discrepant data”, sometimes also referred to as “negative cases”, to mean participant's viewpoints or experiences that differ from those experiences I described above. These contradictions in data can lead to surprising findings, strengthening of our understanding of the coding constructs, and an expanded view of informal physics experiences.

In this chapter, we are looking at individual experiences and so we do expect there to be a difference among those experiences. Each informal physics program facilitator is an individual with their own personal experiences and opinions. However, it is important to note that interview length and the content of the interview can impact the number of codes present in each interview. Some participants went on tangents during the interview, which resulted in portions of the interview transcript without any codes assigned to the data. Below, I show the graphs from Mike and Cecilia's experience along with graphs from the other facilitators we first examined. These graphs are intended to be big picture snapshots of each individual's experience. We are not making any statistical claim about the differences in these graphs and we recognize that the difference in counts is dependent on many variables, some of which were just pointed out. However, the absence of codes for any particular construct may be important to note since that is a difference in experiences.

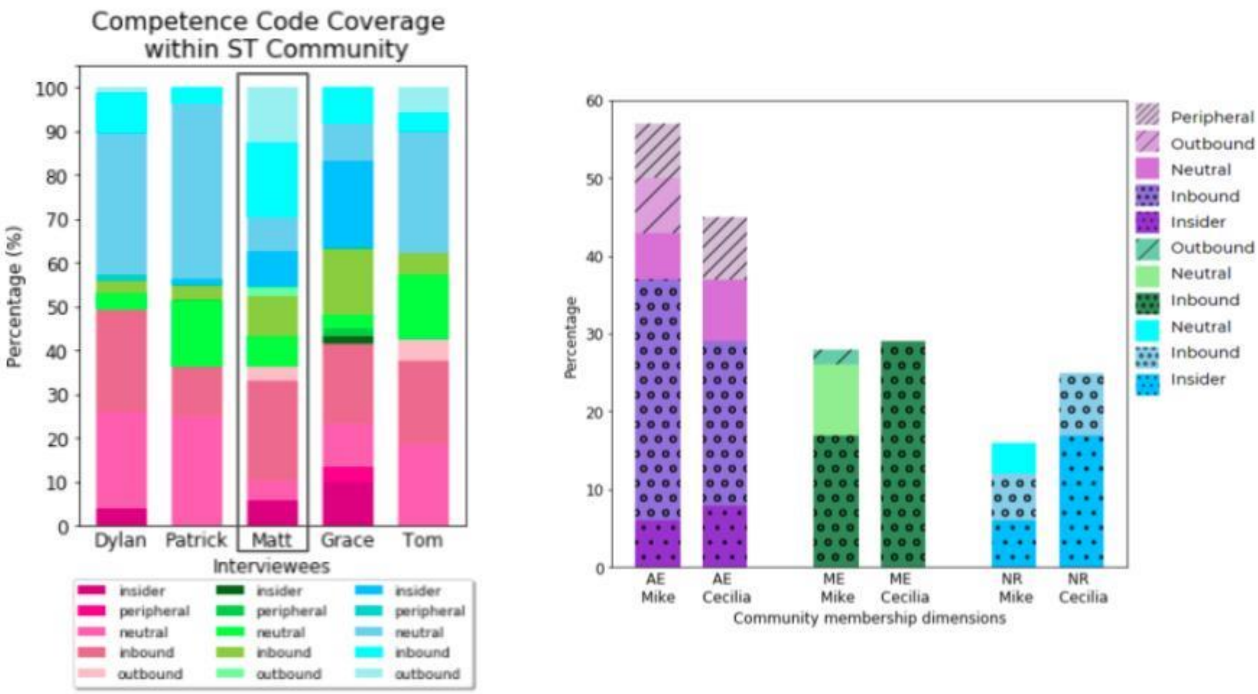


Figure 13: Community Dimensions for Science Theatre (left) and PISEC (right) facilitators. The codes have been separated into the subcode categories to show movement between membership levels.

When starting to look at the three Community Dimension codes, we started with a set of interviews from Matt, a Science Theatre facilitator (noted by the black box in the left graph in Figure 13). Above we discussed the Community Dimensions for two PISEC facilitators, Mike and Cecilia. Looking at just Matt's codes, we expected that Negotiation of the Repertoire would have the most coded segments in the interviews, then Accountability to the Enterprise, and Mutuality of Engagement with the least amount of codes. However, with the PISEC coding, we see the two facilitators having overall different experiences. We see the most amount of Accountability to the Enterprise, some Mutuality of Engagement, and the least Negotiation of the Repertoire. Additionally, when looking at the individual positioning of each facilitator, we see that the PISEC facilitators had much more inbound and insider codes than Matt. This means that during the interview Mike and Cecilia perceived themselves as more central to the PISEC community of practice than Matt did in terms of the Science Theatre CoP.

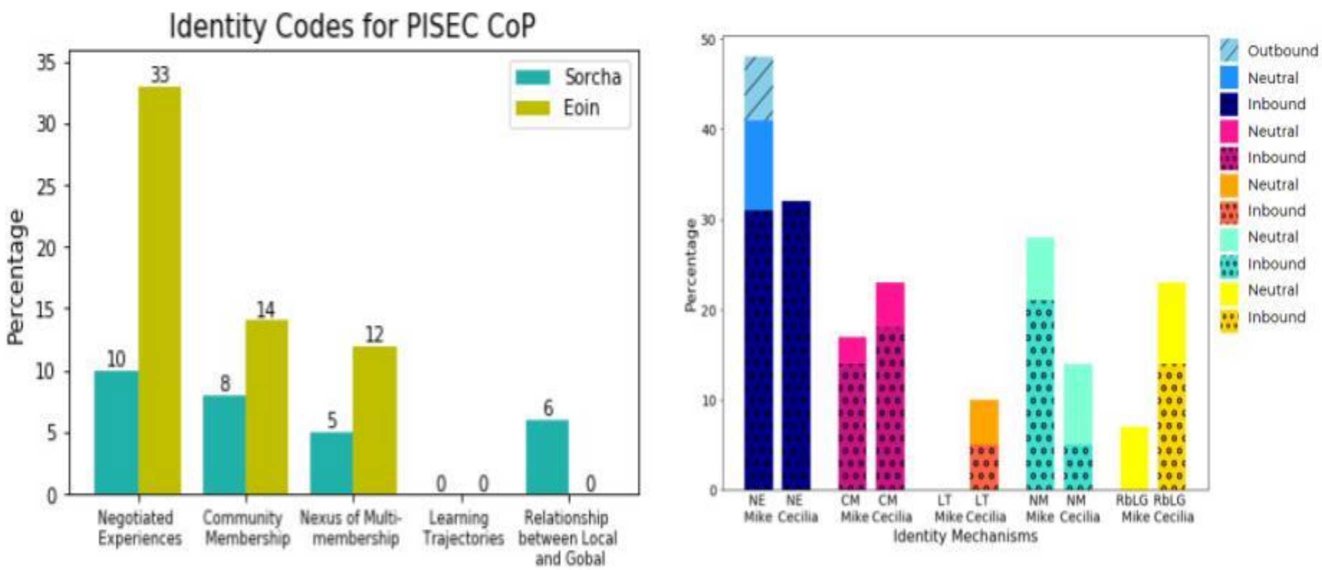


Figure 14: Mechanisms of Identity codes for PISEC facilitators Sorcha and Eoin (left) and PISEC facilitators Mike and Cecilia (right). The codes have been separated into the subcode categories on the right to show movement between membership levels but have not b been separated into subcodes on the left.

When we first started to operationalize the Mechanisms of Identity codes, we looked first at two other PISEC facilitators (shown in the left graph) before looking at Mike and Cecilia (which was discussed above in the bulk of this chapter and shown in the graph on the right). By looking at the graph on the right, you will first notice that Sorcha and Eoin had very different experiences in terms of the number of codes. You will see that neither Sorcha or Eoin had any of their interviews coded as Learning Trajectory. This is different from what we discussed above with Mike and Cecilia. We can speculate that this lack of codes points to Sorcha and Eoin either not experiencing or discussing any past experiences that led to their participation in PISEC.

When thinking about limitations, we can consider that interview participants in these informal physics programs were most likely biased toward those who had a good experience as facilitators. All facilitators within the informal physics programs were invited to participate in the interviews, however those who had a good experience were more likely to agree to an interview. Therefore, our interview data is biased toward those who are more central or moving toward a more central role within the community because they had a positive experience within the community. The bias in this sample means that we do not have interviews with those facilitators who did not have a great experience. However, within the interviews that we have, the outbound or peripheral subcodes are hinting at some alternative experiences that have yet to be discussed.

Matt, the facilitator from Science Theatre whose first interviews were used to operationalize the framework, talked extensively about how he had switched his major to psychology and felt as though he did not understand the science concepts as well as other members of Science Theatre. He said:

> *Now it's kind of weird because I'm in science theater. Everyone's like, "I'm a physics major," "I'm a chemistry major," "I'm a bio-fill-in-the-blank-major." And I'm just over here like, "I'm psychology. I study people but I don't know how-- what is momentum? Why is this spinning wheel doing anything?" I don't know.*

This segment of his interview was coded as outbound Negotiation of the Repertoire because he is describing a more difficult experience with feeling confident around the science knowledge. Matt's thoughts about his science knowledge within the context of Science Theatre is similar to how Cecilia felt about her physics knowledge in graduate school but different from how both Mike and Cecilia felt like experts within PISEC.

Matt was also a newer member of Science Theatre, as opposed to the longer experiences that Mike and Cecilia had within PISEC. He starts off as a peripheral member of the Science Theatre community of practice and describes his lack of experience with "stage shows" which are the main ways that Science Theatre facilitators interact with audience members. He says:

> *I haven't done any stage shows. Which is kind of scary because the entire trip is stage shows. I've never done one. But I've done a lot of hands-on shows and those are a lot of fun.*

This quote from Matt was coded as outbound Negotiation of the Repertoire because he is lacking the experience that other Science Theatre facilitators have had in order to gain the skills necessary to participate in a stage show.

Overall, we speculate that it is most likely to see negative cases or discrepant data among the outbound and peripheral subcodes for both the Community Codes and the Mechanisms of Identity. A more robust data set with less bias could also lead to different experiences among individuals. However, during the next chapter, when data is discussed as the chunk size of the entire informal physics program, discrepant data may include a program that has similar structures that does not seem to support identity development among facilitators. Another possibility for a negative case among entire informal physics programs would be data that leads to programs that are structured differently from the three programs in this study that still lead to similar outcomes. However, we are again limited by our data set being from facilitators in three informal physics programs.

4.11 Conclusions and Implications

We started this chapter asking whether the structured CoP framework was a powerful instrument to understand identity formation within informal programs and how student facilitators view their membership within the program. We see that the operationalized framework allows us to understand how participation in informal physics programs may impact university physics students' identity and sense of belonging within the physics field. The power of this framework is that it allows us to sense where the university students see themselves within the Community of Practice and to learn what aspects of that community impact their involvement. From the point of view of physics identity, this is important because we can understand how participation in informal programs allows for the growth of a physics identity and how these students can become more central members within the physics community. In this framework, our diverse backgrounds and multiple identities represent a key mechanism for identity development, because it is only when our different memberships are able to intersect, collaborate, and work together that we can fully become integral members of a community of practice.

The coded narratives of Mike and Cecilia allow us to understand the connection between the Community Dimensions and the Mechanisms of Identity. The connection between these constructs within the framework shows us how facilitators view their membership within informal programs and what specific program structures influence identity development.

We see that Mike and Ceclia both found the enthusiastic responses of the children as an integral part of their participation and contributing to the feeling that they were making a difference and providing role models to others. Additionally, both Mike and Cecilia seemed to be constantly negotiating between their membership in the physics community and the PISEC community. In part, it is their membership in physics that drives them to engage in PISEC because they want to share their passion but some of the norms and practices of physics conflict with their participation in PISEC. At the same time, Mike and Cecilia's participation in PISEC seems to be shifting their perception of what it means to be a member of the physics community by broadening their personal definition of what constitutes the physics community's practices and who can be in it. Being able to understand what mechanisms influence identity within the community is important for understanding how informal physics programs can support physics students who act as facilitators. When researchers and practitioners have a better understanding of the specific elements of informal programs that are influential, then we can reform and better design future programs.

Therefore if we revisit our research question on whether facilitating informal physics programs can help foster university students' identity, we can use the community dimensions and mechanisms of identity from Mike and Cecilia to understand how the operationalized framework illuminates positive identity development. The framework helped us understand how Mike and Cecilia perceived their membership within PISEC and physics as well as what structural elements of PISEC aided in membership, or identity, growth. Additionally, when considering diversity and inclusion in physics, this operationalized CoP framework could be utilized to understand how specific programs support identity development. We believe that the consequences of this framework reach far beyond the scope of informal environments and that it could be used to understand how physics, as a field, could be inclusive and welcoming to multiple different identities and experiences.

The different operationalized codes of the CoP framework allow us to identify the university students positioning within the informal physics program CoP, the broader informal science CoP, and the physics CoP. We see how these communities overlap in the students' experience. Furthermore, we are able to identify what factors have a bigger influence on these identities, and if there are shifts in their identities through participation. The implications of the operationalization of the CoP framework are relevant not only for informal learning spaces but also for formal learning environments and the physics field at large. These implications can lead to an understanding of what factors have a bigger impact on supporting identity formation and can therefore lead to the design of more inclusive learning environments.

In the next chapter, we analyzed the remaining interviews in our data set as well as use interviews from another program to look at facilitators from a variety of backgrounds, disciplines, and levels within those disciplines, as well as different models of informal programs. We use the collection of many individual experiences to understand the programmatic experience of facilitators in each informal physics program.

CHAPTER 5: FINDINGS FROM EXAMINING ESTABLISHED INFORMAL PHYSICS PROGRAMS WITH THE COP FRAMEWORK

In previous work (Chapter 4), we have postulated that informal physics programs can support physics identity by functioning as a community of practice for undergraduate and graduate student facilitators. We operationalized Lave and Wenger's theoretical Communities of Practice framework so that it was contextualized to the informal physics environment. We then utilized a case study approach to understand the individual experiences of university students who acted as program facilitators within an informal physics program. In using the Communities of Practice framework to understand the experiences of the university students, we were able to learn how individuals navigate their membership and the development of their physics identity within these communities.

In this chapter, we build on our prior work that operationalized the Community of Practice framework, and now apply it to multiple informal physics contexts. We do this to investigate if there are different ways that student facilitators may grow in their identities as members of informal physics communities, as people who do physics, and as members of the broader physics community. We also seek to identify structures and norms of informal physics programs that contribute to positive or negative identity development opportunities within these communities of practice. Thus, we seek to answer two questions: *In what ways can the identities of student facilitators be affected in informal physics programs that are communities of practice? What are structures and practices of informal physics programs that support physics identity development in physics student facilitators?*

To answer these questions, we have conducted an investigation into three different informal physics programs that function as communities of practice. We collected interviews from student facilitators about their motivation and experience participating in the programs. We analyzed these interviews with our operationalized Communities of Practice framework for informal physics programs to determine how these programs may support identity development. From this analysis, we also extracted themes spanning the programs about the key structures and norms that support student facilitators. Results from this study are relevant to both practitioners and researchers who are looking to improve the support given to university physics students and when creating informal and formal learning environments. The following sections are adapted from our published manuscript in Physical Review Physics Education Research [71].

5.1 Establishing Informal Physics Programs as Communities of Practice

In this study, we wanted to apply the operationalized Communities of Practice framework to several different types of informal physics programs in order to document different ways that informal physics groups may provide opportunities for identity development [63]. In selecting our cases, it was a necessary step to determine if an informal physics program did in fact have the characteristics of a community of practice before applying the framework to analyze group members' experiences.

Detailed descriptions of the format and content of each program in this study are in Chapter 3. Broadly, the domain of each program was centered around university students achieving a common goal of sharing physics knowledge with youth outside of the field. The specific practices of each program differ considerably since the format of each program is different. However, all three programs involve university physics students taking some form of leading interactive physics activities with youth.

The community of each program consists of all the student facilitators, staff, and faculty who work together to develop and deliver the program content. One significant consideration here is whether to include the youth participants as part of the community as well. In Science Theatre and Quavers to Quadratics, youth typically interact for only a short period of time with the undergraduate facilitators and mostly receive the physics content by interacting with already developed demonstrations - therefore, we did not include them in the community. However, in PISEC, youth and facilitators meet in small groups weekly over the course of a semester or often an entire year, and they are encouraged to co-create new activities. Due to the extended relationships that are formed in this program, we include youth as part of the PISEC community.

By identifying these three essential elements of a community of practice for each informal physics program (listed in each program description included in Chapter 3) using a practitioner-researcher approach, we have established that all three cases have the necessary characteristics of a community of practice. While the three programs being considered in this work are unique in that they involve undergraduate facilitators interacting with children through physics activities, there may be many other informal physics programs that also contain the elements of a community of practice. This finding is of itself important, as it demonstrates that a diverse range of informal physics programs can serve as an environment for physics students to build identity.

5.2 Understanding Student Facilitator Experiences in Informal Physics Communities of Practice

A case study approach allows us to gain an in-depth and contextualized understanding of facilitators' experiences in the informal physics programs, as well as explore the characteristics, structures, and implications of facilitating informal physics programs for students' physics identity. We followed an interpretative approach to the case study to understand from the individual's point of view the social meaning and participation. To this end, we conducted interviews with students leading these programs (facilitators). Interviews were an appropriate data source because we were looking to explore facilitation experiences through the individual participants' lens alongside their own positionality within their different communities. Interviews were analyzed using the *Community Dimensions* (Table 2) and *Mechanisms of Identity* (Table 3) from the operationalized Community of Practice framework.

5.2.1 Interviews with university facilitators

We collected interviews from 58 participants across the three informal physics programs. These participants were from the pool of those facilitating the activities in the programs and that were willing to participate in the research study. Based on a careful reading of all interviews by multiple members of the research team, we focused on a subset of 18 participants, which correspond to 29 total interviews. Another 4 participants' interviews were used in our previous paper that explored the use of the Community of Practice framework [64]. The reason for this selection was three fold: i) identify the interviews that had descriptive information - some of the interviewees did not provide detailed answers which limited what we could learn from their experiences; ii) allowed similar representation from the three programs because we had many more interviews from one of the programs than the other two; and iii) we selected interviews that represented some diverse aspects of facilitators in the programs - gender identity, undergraduates and PhD students, and postdoctoral fellows - and that the representation reflected the demographics of each program. It is important to note here that it was not possible to include many facilitators of color because the programs generally had white facilitators. Seven participants were from PISEC (7 interviews), five participants were from Science Theatre (10 interviews), and six participants were from Quavers to Quadratics (12 interviews). There are several justifications for using a subset of the full data set for analysis: 1) Consistency of interview protocols - earlier versions of the PISEC protocol differed from the protocols used for the other two programs, because we used PISEC participants to test the different protocols. We conducted three different test rounds of the protocol before arriving at the final version, which is the one used in this study and 2) interviews used in earlier stages to operationalize and validate the framework were excluded from the current study. Each interview within our entire data set was read, or listened to, by members of the research team and the final interviews selected for this paper were intentionally chosen to represent the diversity of the facilitator population within the programs. For more details on the study participants see the Appendix C.

5.2.2 Coding process

Interview data presented in this chapter are from interviews coded with the operationalized Community of Practice framework (described in detail in Chapter 4). The research team took a two-phase approach to coding the interviews which is described in Chapter 3.

5.2.3 Statistical analysis methods

To interpret the data from individual interviews and allow for comparison between the programs, the counts (frequency) of all of the codes from each interview were normalized, i.e., we used percentages to report findings. For each interview, the percentage of each individual code is given with respect to the total number of codes in the interview. For example, in order to calculate the percentage of *Accountability to the Enterprise* for an interviewee from Quavers to Quadratics, we divided the frequency of *Accountability to the Enterprise* codes for the total frequency of *Community Dimensions* codes within that interview. It is important to note here that for the purpose of this study we only looked at the codes that were associated with the program's community of practice. For example, for interviewees from Quavers to Quadratic we only looked at the *Community Dimension* and *Mechanisms of Identity* codes that were coded under the Quavers to Quadratics community. More details about the reported statistics, including what statistical tests were conducted, can be found in the Appendix C. We used statistical analysis to establish a baseline for comparison across the programs. However, as mentioned before, the richness of the data is not only shown through statistical differences but within the narratives. Within the following interview analysis section, we discuss how in some cases the frequency of the code did not reflect the significance of the experience in fostering identity, but the significance comes through the stories the facilitators share. This is particularly evident in the analysis section of intersection between *Community Dimensions* and *Mechanisms of Identity*.

5.3 Interview Analysis

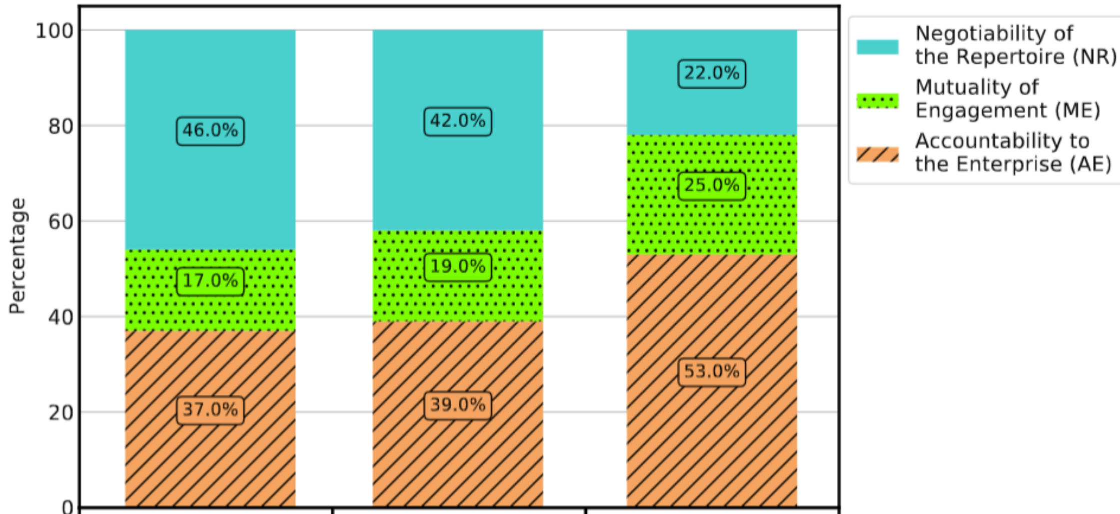
We want to understand how structural similarities and differences between the programs impacted the community of practice and thus the identities of student facilitators. In order to do this, we look at the *Community Dimensions* and *Mechanisms of Identity* codes for each program. We also look at the overlap between these layers of codes; this intersection provides information on whether facilitators' membership within their respective community of practice changed throughout their participation in the community and what aspects of the corresponding program's design may have prompted such changes.

5.3.1 Community Dimensions

From the overall *Community Dimension* codes, we can understand how students perceived their positionality within the programs as well as which dimensions impact their positionality. Figure 15 shows the *Community Dimensions* aggregated for each of the three informal programs. The percentages shown in each bar indicate how many of the codes were assigned to each Community Dimension out of the total Community Dimensions codes per interview, and thus all the bars add up to 100%. The table shows the breakdown of each Community Dimension into the subcodes with the percentage indicating how often the subcode was assigned to a given Community Dimension. One finding to note is there are no statistically significant differences between any of the dimensions for Quavers to Quadratics and Science Theatre. In the case of these two programs, *Negotiability of the Repertoire* - which is related to knowledge of and competence in the practices of the community - represents more than 40% of the *Community Dimension* codes for both programs, making it the most important factor to establish membership. This emphasis indicates that facilitators in Science Theatre and Quavers to Quadratics measure their membership mainly through their knowledge and competence of the repertoire. In contrast, this mechanism is the least represented *Community Dimension* for PISEC (22%).

The second most coded *Community Dimension* for facilitators in Quavers to Quadratics and Science Theatre is *Accountability to the Enterprise*, which represents more than 35% of the codes. We interpret this to mean that to become a central member of the community, students feel they need to actively participate in the practices of the community (*Negotiability of the Repertoire*) and have a clear understanding of the mission of the community (*Accountability to the Enterprise*).

In contrast, *Mutuality of Engagement* represented less than 20% of the codes for these programs, indicating that connecting to other program facilitators is less important for students in these groups. The main difference in the Community Dimension codes between these two programs is seen in the subcode percent (see table in Figure 15). Science Theatre facilitators had higher percentages of neutral codes and Quavers to Quadratics had more *insider* and *inbound* codes across all categories. More *insider* and *inbound* codes for Quavers to Quadratics indicate that the facilitators perceive that they are moving to become a central member of that community.



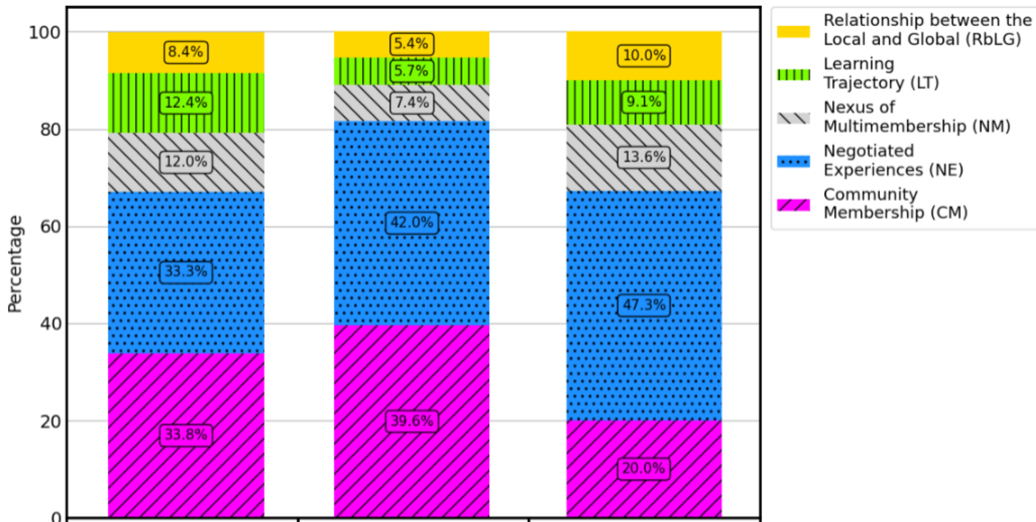
	Quavers to Quadratics			Science Theatre			PISEC		
	AE	ME	NR	AE	ME	NR	AE	ME	NR
Insider	55.5	20.9	38.8	14.0	1.4	13.0	13.1	5.0	0.0
Inbound	28.2	72.1	16.5	53.0	54.8	26.0	57.1	60.0	51.4
Neutral	9.1	7.0	27.3	27.0	39.7	49.0	7.1	20.0	22.9
Peripheral	6.4	0.0	5.8	2.0	1.4	0.6	17.9	0.0	8.6
Outbound	0.9	0.0	11.5	4.0	2.7	11.0	4.8	15.0	17.1

Figure 15: The above graph shows the overall Community Dimension codes for each of the three informal programs (left to right: Quavers to Quadratics, Science Theatre, PISEC).

In contrast to the other two informal programs, for PISEC, *Accountability to the Enterprise* makes up 53% overall of the *Community Dimension* codes. Thus, PISEC facilitators perceived the commitment to the goals (*domain*) of the community as the leading factor for building membership. The majority of the facilitators had a clear alignment with the values of the program and were demonstrating a strong commitment to the program, shown by a majority of *inbound* codes within this dimension. *Mutuality of Engagement* makes up 25% of the codes for PISEC, indicating that connecting to other program facilitators and children is a more important factor for students in PISEC than in the other two programs. *Negotiability of the Repertoire* is the least frequent code (22%), which shows that PISEC facilitators view understanding the practices as the least important aspect of being a member of the group. Reasons for these differences are due to the different structures of the PISEC program and who constitutes the community. These will be expanded on in the next section.

5.3.2 Mechanisms of Identity

While the *Community Dimensions* indicate facilitators' perceived level of membership within the community of practice, the *Mechanisms of Identity* point out how the particular structures and practices of the program might foster movement in perceived membership levels. Figure 16 shows the *Mechanisms of Identity* code distribution for each informal program. The percentages shown in each bar indicate how many of the codes were assigned to each Mechanism of Identity out of all Mechanisms of Identity, and thus all the bars add up to 100%. The table shows the breakdown of each Mechanism of Identity into the subcodes with the percentage indicating how often the subcode was assigned to a given Mechanism of Identity. Across all three programs *Negotiated Experiences* and *Community Membership* are the most salient mechanisms, suggesting interactions and connections made through participation while engaging in the practices of the community support membership and identity development. Differences arise among the programs when we look at the *Mechanisms of Identity* (as compared to the *Community Dimensions*). While all three of the programs have similar missions (*domains*), each has a unique way of carrying out this mission. This variety of program structures is reflected among the *Mechanisms of Identity* distributions, which will be discussed in detail in the following sections.



	Quavers to Quadratics					Science Theatre					PISEC				
	CM	NE	NM	LT	Rb LG	CM	NE	NM	LT	Rb LG	CM	NE	NM	LT	Rb LG
Inbound	60	80	81	57	95	50	72	52	84	89	68	65	33	70	64
Neutral	32	19	15	43	5	41	19	36	16	6	23	23	40	30	36
Outbound	8	1	4	0	0	9	9	12	0	6	9	12	27	0	0

Figure 16: The above graph shows the overall Mechanisms of Identity codes for each of the three informal programs (left to right: Quavers to Quadratics, Science Theatre, PISEC).

5.4 Intersections between Community Dimensions and Mechanisms of Identity

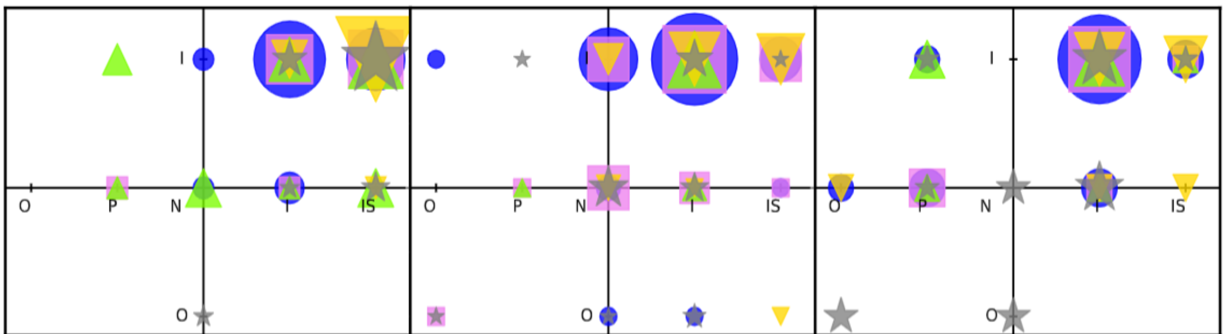
In order to gain a more thorough understanding of facilitator experiences within each program, we now look at the interactions of the *Mechanisms of Identity* with the *Community Dimension* codes. These intersections give insight as to which structural elements within the programs impact facilitator perception of their membership and their identity.

To map the intersections, we looked at the overlap in counts between the Mechanisms of Identity and each Community Dimension. We then graphed these values on a pseudo-scale that divides the interaction between *Mechanisms of Identity* subcodes and one of the *Community Dimensions* into four quadrants (see Figures 17-19). The X-axis has subcodes for the *Community Dimensions* going from left to right, ranging from *outsider* to *insider*. The Y-axis scale was determined by the *Mechanisms of Identity*, ranging from *outbound* to *inbound*, going from bottom to top. (See the Appendix C for more details). Different shaped markers were used for each of the mechanisms, with the size of the markers representing the normalized frequency (percentage) of the interaction. Plotting the data in this way allows us to visualize which mechanisms are most prevalent with respect to the inbound/insider community of practice experiences (and likewise outbound/outsider experiences). For example, the markers in the upper right quadrant (region shaded green on the table) indicate *Mechanisms of Identity-inbound*/*Community Dimensions-insider* interactions and markers in the lower left quadrant (region shaded red on the table) show *Mechanisms of Identity-outbound*/*Community Dimension-peripheral* interactions. Below, we discuss the key interactions (seen by the larger markers in Figures 17-19) for each of the three *Community Dimensions* through quotes from the facilitators (using pseudonyms) to narrate which aspects of program design impacted the facilitator's identity.

5.4.1 Intersection with Accountability to the Enterprise

Figure 17 shows how *Accountability to the Enterprise* intersects with all five of the *Mechanisms of Identity* constructs in each of the three programs. Having all five *Mechanisms of Identity* interact with the *Accountability to the Enterprise* demonstrates that facilitators see an alignment of their values and commitment to the mission of the program and how that impacts all areas of their membership. We consistently saw that the connection with the *domain* (mission) of the community was a significant aspect of a facilitator's choice to participate in an informal physics education program. This can be appreciated in the upper right-hand quadrant for all three programs in Figure 17.

The high level of commitment from the facilitators is seen through the high percentage of the *inbound* and *insider* subcodes within the *Accountability to the Enterprise* code (more than 67% for all programs) shown in the upper-right quadrant of Figure 17. However, we also see that *Community Membership*, *Learning Trajectory*, and *Relationship between Local and Global* are the mechanisms that interact with this community dimension most frequently. We discuss some of these interactions in the context of the programs below (with more information in the Appendix C).



		Quavers to Quadratics					Science Theatre					PISEC				
		Outbound	Peripheral	Neutral	Inbound	Insider	Outbound	Peripheral	Neutral	Inbound	Insider	Outbound	Peripheral	Neutral	Inbound	Insider
Inbound	NE o	0	0	1	12	8	1	0	8	18	4	0	2	0	17	3
Inbound	CM □	0	0	0	5	7	0	0	4	10	4	0	0	0	9	2
Inbound	LT △	0	2	0	4	7	0	0	0	7	0	0	3	0	6	2
Inbound	RbLG ▽	0	0	0	3	16	0	0	2	6	6	0	0	0	6	5
Inbound	NM ☆	0	0	0	3	12	0	1	0	4	1	0	2	0	8	2
Neutral	NE o	0	0	1	2	0	0	0	1	0	1	2	3	0	3	0
Neutral	CM □	0	1	0	1	0	0	1	4	2	1	0	3	0	2	0
Neutral	LT △	0	1	3	1	3	0	1	0	1	0	0	2	0	2	0
Neutral	RbLG ▽	0	0	0	0	1	0	0	1	1	0	2	0	0	2	2
Neutral	NM ☆	0	0	0	1	2	0	0	4	2	0	0	2	3	6	0
Outbound	NE o	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
Outbound	CM □	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Outbound	LT △	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Outbound	RbLG ▽	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Outbound	NM ☆	0	0	1	0	0	1	0	1	1	0	3	0	3	0	0

Accountability to the Enterprise

Figure 17: The above figure shows the intersection of the Accountability to the Enterprise - Community Dimension subcodes (x axis) with all five of the Mechanisms of Identity and their subcodes (y axis). Each mechanism is represented by a different color and shape as shown in the second column of the table.

Negotiated Experiences (shown by the blue circle in Figure 17) is seen frequently interacting with *Accountability to the Enterprise* and accounts for the majority of the inward movement in membership among facilitators. For example, in PISEC, the connection with children is more impactful than those with other peers, community partners, or members of the community as they build long-term relationships with the children and seeing the effect on their lives makes the facilitators “hopeful” and really enjoy the experience. This was explicitly stated earlier as Lily, a physics graduate student volunteering in PISEC, discussed how interacting with the children increases her excitement about physics (as seen in the quote included in the "Coding the Interviews" section).

Similarly, for Science Theatre the common themes from the interactions of *Accountability to the Enterprise* and *Negotiated Experiences* are related to how the facilitators enjoyed the children being really engaged, asking questions, getting involved, and expressing that they think science is cool. Tom, an undergraduate student, shared when asked about his experience with children reacting to the demos:

> *And then, being able to share the science to little kids is really awesome, 'cause I love science, so having the idea that I might inspire a little, or a kid, to even just think something that I did was cool, that's science related.*

This quote was coded as *inbound Accountability to the Enterprise* and *inbound Negotiated Experiences* because, like Lily from PISEC, Tom enjoys the children's positive reaction to the shows and the idea that he might be inspiring children to continue participating in physics or science (Science Theatre *domain*). These ideas make participation in the Science Theatre community valuable to him and therefore supports his inward movement in the community. Additionally, it reaffirms his passion for science - supporting his science identity.

The engagement and excitement children show while engaging in the activities is a source of motivation and inspiration for many of the Quavers to Quadratics facilitators. Emer, a science education major, was asked if she thought she was having an impact on the children when she shared:

> *I definitely feel like I'm making some sort of meaningful connection which, like, is such a great thing to see because that's obviously the aim of it... And when I see the*

kids thinking: 'Oh my God this is amazing! I didn't know or think of it this way!' or you know like seeing them, they connect vibrations and amplitude together, and those two things [are] both scientific… You can see that they are more and more convinced each time [about the connections between physics and music].

This reflection, coded as *inbound Negotiated Experiences,* about how enjoyable it is to see children at the end of the workshop connecting the concepts of music and physics, which is the Quavers to Quadratics *domain.* Therefore the facilitator experience translates into *insider Accountability to the Enterprise,* which is fostering inward membership movement.

Community Membership is the second most coded *Mechanism of Identity* overlapping with *Accountability to the Enterprise* (shown by the pink square in Figure 17) and tracks how facilitators' confidence in the practices of the community impact their membership. This identity mechanism is related to elements of the structural design of the program; in the case of Science Theatre, this would be related to the community-built collection of demonstrations and show scripts along with the physical spaces that the group has to hold meetings. Science Theatre facilitators are undergraduate students from various different backgrounds and areas of study including both science and non-science majors. Therefore, they have a considerable amount of content to master, as well as needing to learn how the demonstrations work and the phenomena behind them. For example, Liam, an undergraduate student whose background is not in physics, stated that he feels like a science person because he asks a lot of questions when asked if he identifies as a scientist:

But I was asking questions like, this dixie cup demo worked really really well. Does it have to be paired with the bed of nails? Could you do Bed of Nails with dixie cups and then have another part, just have the dixie cups demo. Because you could do *that. That demo in and of itself is pretty great… I was asking a lot of practical questions where I'm like, in practicality, how can we make this work better? How can we explain this to where it makes more sense?*

In this quote, Liam is explaining that he is insistent in learning the content and practices of the program by asking his peers (*Community Membership*). Liam's questions show his growing knowledge of and confidence with the Science Theatre practices so this segment was coded as *inbound Accountability to the Enterprise* and *inbound Community Membership*. He goes on to explain that he cares more about making the experience better for the children and assuring that they do not leave with misconceptions even if they do not remember the concepts. He does this because he cares about the experiences the children have in the program and making science fun and understandable (part of the domain of Science Theatre).

Relationship between Local and Global (shown by the yellow triangle) and the *insider* subcode for *Accountability to the Enterprise* also frequently, as seen in Figure 17. This mechanism relates to the connection between participation in the local community and participation in a broader (global) community of practice. Developing awareness of those connections requires a deep understanding of the domain of the local community and how it plays a role in a global perspective.

Across the programs the main theme identified in segments coded as *Accountability to the Enterprise* relates to the facilitators' wish to be part of a community focused on encouraging children to enter STEM fields. For many interviewees, being involved with Science Theatre provided a bit more than just a way to satisfy their physics curiosity, it provided a chance to share physics with others. For example, Grace, an undergraduate who has been involved in Science

Theatre for several years, connects her interest and involvement in Science Theatre to her other identities and shares how this intersection is important to her:

> *I really like [Science Theatre] because it's like a chance to reach out and spread what you're passionate about, and I think that, especially as a woman of color, I want to see more people in science in general. Especially reaching out to young girls, young girls of color. Because, you know, science can be very monolithic and when you do outreach you get more types of people.*

In this case, Grace's statement was coded as *insider Accountability to the Enterprise* because she is connecting her value of wanting to be a role model for women of color in physics within Science Theatre's mission to provide fun and engaging physics experiences for everyone. This portion of Grace's interview was also coded as *inbound Relationship between Local and Global* because she is describing how her participation in Science Theatre can have a broader impact on the physics/science community at large, regarding issues of underrepresentation.

In the case of PISEC, the facilitators are already committed to the physics community and its value, given that they are mostly PhD students working toward research that will add to understanding phenomena, so what PISEC allows them to do is communicate their passion for physics to children. As Evan, a physics graduate student, gives the following answer when asked why they first volunteered for PISEC:

> *I've kind of really grown to [where] I would do PISEC now even if my boss told me I didn't have to, just because I feel like it's a great idea to give back to the community and to kind of just be there as someone who can say 'hey, science is cool.' Because I didn't have anybody when I was that age telling me science was cool, so I feel like*

taking just an hour and a half out of your time, out of your day, and kind of just introducing the world of science to some kids is a good thing, is a fun thing to do.

This portion of the interview was coded as *insider Accountability to the Enterprise* and *inbound Relationship between Local and Global* because there is an indication of a commitment to participate in the community, regardless of the implications and therefore perceiving the value of doing outreach. Evan is reflecting on how he would have liked the opportunity to participate in a program like PISEC as a child, and that is something that he can contribute now.

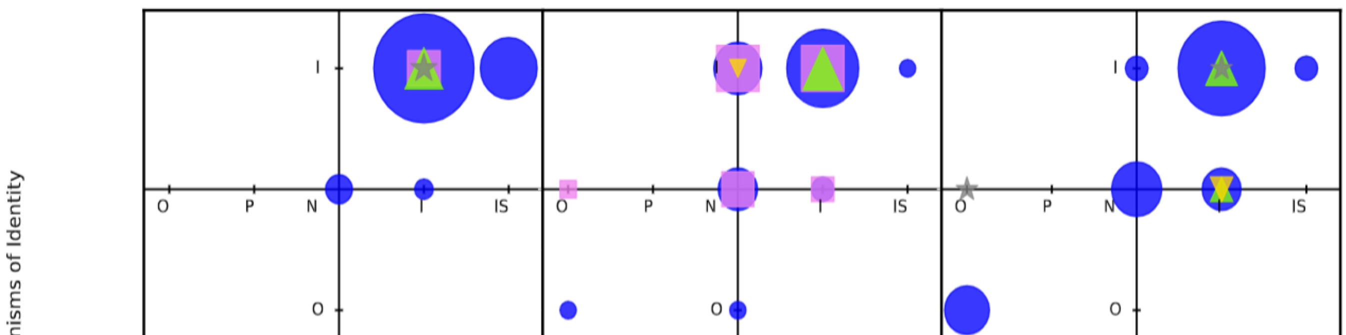
In Quavers to Quadratics, student interviews show that the facilitators hold similar views to their PISEC and Science Theatre counterparts around the importance of the program's values, as said by Seán, an undergraduate physics major:

I mean I have always been a big believer in outreach, and I think it's very important especially for scientists to do. Maybe I am biased because I am involved in science, but it's affected how I view it and I think I can put more emotion into it now because I [have] taken part in [outreach]... But I have always been a big believer in outreach so it didn't change that in any way shape or form but yeah I understand now there is more emotion behind that and how gratifying it can be.

This quote from Seán was coded as *insider Accountability to the Enterprise* and *inbound Relationship between Local and Global* because he is explaining how he sees the value of the outreach community and how that intersects with the domain of the physics/science community. Sean is also narrating how participation in Quavers to Quadratics has reaffirmed the positive feelings related to being a member of the science outreach community.

5.4.2 Intersection with Mutuality of Engagement

Mutuality of Engagement is related to interactions between community members, the norms of those interactions, and how we recognize and are recognized as members of the community of practice. Therefore, it is expected it would have more interaction with the *Mechanisms of Identity* related to interactions with other members of the community such as *Negotiated Experiences* and *Community Membership*. This is confirmed in Figure 18, where the majority of the interactions for all three programs are associated with these *Mechanisms of Identity*.



Mechanisms of Identity		Quavers to Quadratics: Outbound	Peripheral	Neutral	Inbound	Insider	Science Theatre: Outbound	Peripheral	Neutral	Inbound	Insider	PISEC: Outbound	Peripheral	Neutral	Inbound	Insider
Inbound	NE o	0	0	0	57	18	0	0	13	29	2	0	0	3	43	3
	CM □	0	0	0	6	0	0	0	10	10	0	0	0	0	0	0
	LT △	0	0	0	8	0	0	0	0	9	0	0	0	0	6	0
	RbLG ▽	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
	NM ☆	0	0	0	4	0	0	0	0	0	0	0	0	0	3	0
Neutral	NE o	0	0	4	2	0	0	0	9	3	0	0	0	14	7	0
	CM □	0	0	0	0	0	2	0	6	3	0	0	0	0	0	0
	LT △	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0
	RbLG ▽	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0
	NM ☆	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0
Outbound	NE o	0	0	0	0	0	2	0	2	0	0	11	0	0	0	0
	CM □	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	LT △	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	RbLG ▽	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	NM ☆	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Mutuality of Engagement

Figure 18: Showing how the Mechanisms of Identity overlap with the Mutuality of Engagement. The frequency of the overlapping is represented by the size of the markers. The table mirrors the plot and shows the frequencies in each quadrant marked with different colors.

Negotiated Experiences (shown by the blue circle in Figure 18) represents one of the most often mentioned mechanisms to build identity within the communities of practices observed here. The relationships with other members of the community, whether the children, partners, or peers, fosters and supports facilitators' membership. Feeling supported and recognized by their peers provided a stepping stone for newer members to venture into becoming more central members. The excitement and engagement children showed towards physics was a contagious feeling that reminded facilitators of their passion for physics and encouraged them to continue participating and become more central members of the community. This is consistent with other identity frameworks where being recognized as a member of the community has been proved to be one of the main aspects of building identity [21]. This is true for the programs' community of practice as well as the discipline's community of practice. Through participation in the informal physics communities, children and peers recognize the facilitators as members of the programs' community of practice and as experts of the discipline (physics) community of practice.

Moreover, the majority of the *Mutuality of Engagement-Negotiated Experiences* interactions are on the upper-right quadrant, meaning that *Negotiated Experiences* is fostering a movement inward for the *Mutuality of Engagement* dimension. There are some outward interactions of *Mutuality of Engagement-Negotiated Experiences*, mostly for PISEC and Science Theatre which are related to instances where facilitators were having a hard time engaging the children with the activities. However, the facilitators expressed that positive interactions would always outweigh the inevitable frustrations.

We observe that *Mutuality of Engagement* is the least coded *Community Dimension* for Quavers to Quadratics and Science Theatre. A reason for this smaller number of codes is related to identifying who is considered a member of the community of practice. In the case of Science Theatre and Quavers to Quadratics, the children are not regarded as members of the community, while for PISEC they are, which comes from the design of the programs. In PISEC, facilitators interact with the same group of children for one hour a week, for at least one semester, developing important bonds and relationships. The children are co-creators of the activities because they decide what they want to do and how, and the facilitator is there to provide support. The format of Science Theatre and Quavers to Quadratics means that children interact with the facilitators for a very short period of time and while there is some degree of participation from the children in how the activities developed during that time, there is more structure established by the facilitators on what will be done and how.

However, both in Science Theatre and Quavers to Quadratics facilitators spend more time working together as they develop and practice the activities or during the trips. These interactions allowed facilitators to be supported by their peers when learning the norms, content, and practices of the program. In the case of Science Theatre, newer facilitators expressed a general sense of support by the officers and returners because all of the more experienced members were happy to provide guidance and help where needed. For example, when Daisy, an undergraduate student who is in her first year doing Science Theatre, is asked what has participating in Science Theatre meant to her, she talks about her interactions with other members:

> *I went with [Jean] -- but she has been to other [Upper Peninsula] trips. She's super enthusiastic about all of the demos that we do, and it was really too cool to have her as my first person to have a show with, 'cause she taught me a lot.*

This was coded as *inbound Mutuality of Engagement* and *inbound Learning Trajectory* because for Daisy it is clear that Jean's enthusiasm for the program and the mentorship that she provided helped Daisy feel supported and build her membership in the community.

For both Science Theatre and Quavers to Quadratics, the trips (to rural Michigan and rural Ireland respectively) provided good opportunities for bonding outside of the regular practices of presenting the demos and facilitators mentioned how these interactions were positive in helping create connections inside and outside the community of practice. For example, Grace explains that bonds built between Science Theatre colleagues due to the time spent in the cars helped them create a rapport and trust that they relied on during the presentations causing codes of *Mutuality of Engagement inbound* and *Negotiated Experiences inbound*:

> *Because we'd spend a lot of time in the car [laughter]. It's like no way you can't bond when you're in the car that much and spending that much time with each other. And during shows, things happen, so if something goes wrong, you have to rely on each other.*

Similarly, when asked about highlights of the Quavers to Quadratics Galway trip, Orla, an undergraduate physics major, expressed:

> *In terms of the social side of things, it was really nice to bond as a group and I think we got really close with the Galway people. It just worked really well.*

This was coded *insider Mutuality of Engagement* and *inbound Negotiated Experiences* as it shows that Orla developed relationships with her fellow facilitators and enjoyed the bonding process; viewing herself as a central member of the community had a positive effect on Orla's identity.

On the other hand, for PISEC, the most relevant interactions come from the personal relationships that facilitators were able to build with the children over a semester(s), with the majority (65%) supporting an inward trajectory in membership. When asked about the most important thing gained from her involvement with PISEC, Lily discusses how interacting with the children and their enthusiasm makes her move to a more central position in the PISEC community but also influences her membership in the physics community by increasing her commitment to the domain:

> *And then also just like being with the students in PISEC and like being around their excitement and enthusiasm helps me be, like I said earlier, kind of like more excited about physics. Like wow, this is really cool, like this is why I love physics is because of these cool things that I get to learn with like middle school students.*

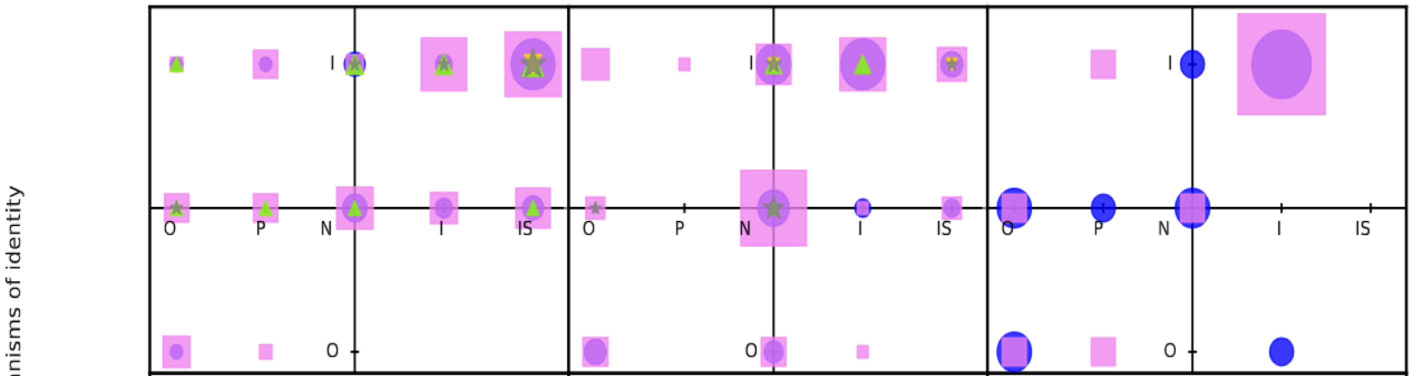
These thoughts from Lily were coded as *inbound Mutuality of Engagement* and *inbound Negotiated Experiences*. She then continues to say what she has gained from her participation, "I guess like as far as PISEC goes, just feeling like I'm a member of this community, like the CU middle and elementary schools. This kind of like community connection, just feeling like I'm a part of that is a big thing that I gained I would say."

Furthermore, facilitators described how the interactions with the children came as a refreshing change of scenery and perspective, compared to their everyday physics community of practice. For example, Ava mentions how much she enjoyed having to work with a group of girls in PISEC because in her everyday physics PhD work, she has mostly male colleagues "[I]t was great because my group was always girls, and I really loved that because like here I'm just interacting with males, males, males all the time." This was coded as *Mutuality of Engagement inbound* and *Negotiated Experiences inbound* as Ava's positive interactions with members of the PISEC community potentially moved her to a more central member of the PISEC community of practice and intersects with her physics community of practice

Unlike in Science Theatre and Quavers to Quadratics, interactions with fellow facilitators were not discussed much in PISEC, possibly because facilitators only shared car journeys to and from schools and the occasional social event. However, other interactions that did affect PISEC facilitators' membership in both PISEC and the physics communities of practices were with their PhD advisors. For example, Evan, a physics graduate student, says "so it started out with my [research advisor] telling me that I should volunteer for PISEC, but as it went on, I really started to kind of enjoy the interaction with the students." This quote was coded for *inbound Mutuality of Engagement* and *inbound Negotiated Experiences* because it demonstrates that supervisors' support can impact the students' physics identity and their participation in the PISEC community. Unfortunately, some PISEC facilitators did not receive this support, like Ava, a physics graduate student, who said she "never really had a lot of positive [encouragement] - in fact my advisor was kind of like not that supportive of doing outreach, because he was like 'yeah it's good but you should get your PhD first' kind of thing" which was coded as *outbound Mutuality of Engagement* and *neutral Nexus of Multimembership*. However, Ava continued with PISEC as "it was really fun. And the kids were really enthusiastic, so that was great," which was coded with *inbound Mutuality of Engagement* and *inbound Negotiated Experiences.* Ava's experience shows how lack of advisor support made her doubt her participation in PISEC, but because she enjoyed working with the enthusiastic children she continued in the program.

5.4.3 Interactions with Negotiability of the Repertoire

Negotiability of the Repertoire is associated with members' competencies and knowledge in the skills, practices, and norms of the community. Therefore, we expect that it would interact more with the Mechanism of Identity – Community Membership, which relates to how we learn the practices of the community through interactions with members, as seen in Figure 19.



		Quavers to Quadratics					Science Theatre					PISEC				
		Outbound	Peripheral	Neutral	Inbound	Insider	Outbound	Peripheral	Neutral	Inbound	Insider	Outbound	Peripheral	Neutral	Inbound	Insider
Inbound	NE o	1	1	2	2	10	0	0	6	10	3	0	0	3	18	0
	CM □	1	3	2	11	16	4	1	6	11	4	0	3	0	39	0
	LT △	1	0	2	2	2	0	0	1	1	0	0	0	0	0	0
	RbLG ▽	0	0	0	0	2	0	0	0.6	0	0.6	0	0	0	0	0
	NM ☆	0	0	1	1	4	0	0	1	0	0.6	0	0	0	0	0
Neutral	NE o	0	0	3	2	2	0	0	5	1	1	6	3	6	0	0
	CM □	3	3	7	4	6	2	0	22	1	2	3	0	3	0	0
	LT △	1	1	1	0	1	0	0	1	0	0	0	0	0	0	0
	RbLG ▽	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	NM ☆	1	0	0	0	0	1	0	3	0	0	0	0	0	0	0
Outbound	NE o	1	0	0	0	0	3	0	2	0	0	6	0	0	3	0
	CM □	4	1	0	0	0	3	0	3	1	0	3	3	0	0	0
	LT △	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	RbLG ▽	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	NM ☆	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Negotiability of the Repertoire

Figure 19: Showing how the Mechanisms of Identity overlap with the Negotiability of the Repertoire. The frequency of the overlapping is represented by the size of the markers. The table mirrors the plot and shows the frequencies in each quadrant marked with different colors.

Community Membership is the most frequently coded *Mechanism of Identity* for Science Theatre and Quavers to Quadratics (39% and 34% respectively). Both programs place emphasis on university facilitators becoming more central members of the community through learning how to do the physics activities. There is also an emphasis on the performative aspect, which is mentioned by Liam while in his first year with Science Theatre:

> *There [were] a lot of demonstrations where I kind of understood them. Like, when someone explained it to me, I'm like yeah, that makes sense. But it's a whole different thing, someone explaining this is how you derive X as opposed to you explaining this is how you derive X.*

This reflection was coded as *inbound Negotiability of the Repertoire* because Liam is explaining that there is a difference in understanding the content and explaining the content, especially to younger kids. He is moving towards becoming a central member as he develops those skills, and his identity within Science Theatre and science is growing as his competence with the practices develops, captured by the *inbound Community Membership* code.

The coded interactions that occur in the upper-right quadrants of Figure 19 (*inbound* and *insider* codes) indicate that facilitators' identities are supported through participation in the practices of the community as well as learning the practices through interactions with other members. Ciara, an undergraduate student new to Quavers to Quadratics, shares the following when asked what she is gaining from being involved:

> *I'm getting a lot of confidence. Like personal confidence and the fact that [I] don't shy away from [it all, when] we're starting off. I didn't know [about] sound waves or frequency or anything like that. You have to just take the challenge and it's really rewarding to see the kids understand different concepts.*

This was coded as *inbound Negotiability of the Repertoire* - Ciara's positive approach to learning the physics content allowed her to successfully teach it to the children, which in turn caused an increase in her personal confidence. This confidence boost produced an inward movement in her membership in both the Quavers to Quadratics community and the physics community (*inbound Community Membership)*.

Science Theatre members also discuss their repertoire by speaking about how they have discovered better ways to communicate about the demos and activities unique to the program. For example, Jacob, an undergraduate student, explains that using physics jargon does not necessarily add to the understanding of the phenomena:

> *We have another one, another Physics demo, that you just don't bring up mass, because mass is-- you can say in all these equations, there is mass, but trying to get a little kid to understand what mass is, is not worth it. And all the mass cancels out anyway [laughter], so you're never going to be, 'Okay, we've done this experiment, having Sally spin around on the chair. Now we're going to do a massless spinning.' Like no, that's-- so yeah, it's just figuring out what to bring up and stuff like that. And so I think as the week went on, I definitely got a better sense of like, okay, judging my audience and figuring out what they could handle.*

This was coded as *inbound Negotiability of the Repertoire* because he is describing how through the process of participating and engaging in the practices of the community, he was developing more confidence and competence in those practices. Jacob's growing confidence affects his identity positively and so was coded as *inbound Community Membership***.**

Negotiability of the Repertoire represents only 22% of the *Community Dimensions* in PISEC (see Figure 15 for details). Unlike in Science Theatre and Quavers to Quadratics, the PISEC facilitators are graduate physics students with a strong foundation in undergraduate level physics, of which the PISEC activities are based on. Also, the model of the PISEC program requires less performance than the other programs. Rather, PISEC activities are more exploratory and one-on-one, with facilitators working alongside children on hands-on activities to try to answer questions. Thus, in PISEC, facilitators do not need to act as experts in front of a crowd but rather as coaches with the children, which de-emphasizes the importance of expert physics content knowledge. This feature is reflected in the absence of codes related to learning the content; facilitators instead focus on the practices related to learning to communicate the content appropriately for their audience, as discussed by Lily:

> *Well one thing, I think it's really important for physicists to be able to explain their work, and physics concepts in general, in a simple way to young kids or to people who are not familiar with physics, and that's really hard to do. So like when you first do PISEC and you have to [make a video for kids communicating about your research] - I think it just takes a bunch of practice I think. And I often find family members or friends who never learned physics will ask me stuff about physics, like 'what is physics, what do physicists do, what do you do?' and sometimes it's really hard for me to explain it in a way that is accessible. So, I think being involved in these types of programs is really helpful for that.*

Lily's comments show a growing understanding of PISEC practices and developing confidence about how she can explain physics, coded as *inbound Negotiability of the Repertoire* and *inbound Community Membership.* She sees knowing how to communicate with the audience as an important practice for being a member of the PISEC community, but also identifies those practices as part of the physics community repertoire. Her improvement in those practices produces inward movement into both those communities.

Negotiability of the Repertoire has the largest percentage of outbound codes for all three programs - representing about 20% of the overall *Community Membership* codes (see table in Figure 15 for details). The outbound codes mainly reflect the challenge of developing practices that lie outside a facilitator's area of expertise. For example, in Quavers to Quadratics, Ciara, a facilitator with no science background, expressed “So we were actually a team of musicians put together but at first it was a bit daunting, with the science aspect”, which was coded as *Negotiability of the Repertoire outbound* and *Community Membership inbound*. However, she then continues to say “actually it worked to our advantage because we found our own way and we kind of made our lesson plan to see the way that we were looking at things” which was coded *Negotiability of the Repertoire insider* and *Community Membership inbound* showing the development of Ciara's confidence with the Quavers to Quadratics practices. In Science Theatre, the large majority of outbound codes came from one student who did not have a science background; it is understandable that a particular student might find the practices more challenging than someone with prior knowledge of the content. In general, outbound codes tended to come from newer members of the community, demonstrating the need to support newcomers and scaffold their inward trajectory within the communities of practices.

5.5 Discussion

Our analysis of the three presented informal physics programs indicate that there are particular structures and practices within these programs that can support physics identity development. It is important to us (and is a call for action within the field of informal science education [78]), that research results should be useful to practitioners working within informal spaces. Thus, in this section, we combine our practitioners' knowledge (which we used to establish the CoP attributes of each program as described earlier) along with the findings from the coding to pull out themes that can suggest practical changes within existing or future informal programs.

Figure 20 shows several main themes that emerged across the three programs in our study. These structures are not comprehensive or necessarily applicable to all programs; however, we do think that they provide a starting place for connecting the communities of practice analysis to concrete aspects of program design and implementation. We discuss how the data connect to these structures, and how these structures may be used by practitioners to consider changes to their local programs.

Figure 20: Identified structures that support facilitators' identity based upon the interview analysis. These structures are general, and practitioners are encouraged to consider other program specific features. The color of each hexagon indicates the Community D Dimension or Mechanism of Identity that each structure is connected to (e.g., Teamwork is in green as it connects to Mutuality of Engagement).

A major theme across the three programs highlighted by the *Accountability to the Enterprise* code and the *Relationship between Local and Global* code is the importance of having a program mission that aligns with the values of the facilitators. Across our data, facilitators expressed a strong desire to participate in informal physics programs as a way to have a physics experience outside of their coursework and research that aligns with their personal values. Many facilitators discussed their desire to participate in informal programs prior to joining them, some even selecting the university they attended based on the informal programs available. Facilitators were highly committed to sharing their physics knowledge and their passion for physics with younger students, especially girls and youth of color, or students who may not have access to physics due to rural settings or socioeconomic status. They talked about wanting to be role models through their participation. Furthermore, many facilitators spoke about how they did or did not have access to informal programs when they were young and how this inspired them to make sure others did have this opportunity. Thus, having a strong mission and communicating clearly about that mission is a key structural component of the programs in our data set.

Another theme is that interaction with the audience is critical for positive identity development for the facilitators. We saw this theme within the intersection of the *Negotiated Experiences* identity mechanism with all three *Community Dimension* codes. Facilitators join a program because they connect with the mission of the program and the mission aligns with their identities. However, it is their enactment of these missions through engagement with the audiences that moves them inwards in the community. Additionally, one result seen from our data set, which includes student facilitators being interviewed at multiple time points, is that more extended and deeper interactions with the audience may have been a bigger contributing factor to the development of facilitators' identities. In PISEC, facilitators really enjoyed building relationships with children over time doing co-constructed physics activities. In Quavers to Quadrics and Science Theatre, facilitators also feel a kind of relationship with their audience, especially in seeing the effect of their program on children. Additionally, when student facilitators feel like they are using their expertise to help others, they are more likely to move inbound in the community, similar to what has been shown in the formal setting with Learning Assistants [54-55]. Thus, our data show that the interactions between the children and facilitators are the most important aspect of the program for facilitators. This finding is consistent with other research in which recognition (both internally and through external validation) as a member of a community of practice can be a determinative factor for identity development [64, 75, 79].

Another important program structure is a supportive schedule, since facilitators worry about fitting informal physics into their busy schedules. We saw this theme emerge from the *Nexus of Multimembership* and *Accountability to the Enterprise* codes, as some PISEC facilitators experienced conflict between their desire to participate in the program, their academic schedules, and the pressure they felt to devote most of their time to research. Our analysis showed the facilitators really wanted to commit to informal programs as they saw the benefits, but time away from work was a concern. This worry caused a negative impact on the facilitators' identities and led some to reconsider their involvement. Support for the informal physics program from leaders at their home institution (e.g. director of physics center, research advisors, professors in classes) was crucial for some student facilitators for inward movement in the physics community of practice because they perceived that public engagement is a practice that physicists should engage in. Practitioners of informal programs may be able to help with this issue by being aware of their facilitators' other commitments and trying as much as possible to work around them. Flexible and thorough training is another structure we identify that stems from facilitators' *Negotiability of the Repertoire* and *Community Membership*.

A frequently mentioned issue, especially for new facilitators, was the anxiety they initially felt learning the practices in the programs. For Science Theatre and Quavers to Quadratics this stress was mainly due to the performative nature of the programs' practices and the need to learn new physics content. The anxiety they felt about their perceived lack of knowledge sometimes negatively affected their identity development and their position within the community, both in physics and in the corresponding program. However, some facilitators struggling in this arena reported that training sessions and working with more experienced members of the community were helpful to overcoming this anxiety and actually developing their skills. Thus, flexible and thorough training that involves more central community members is a key structure to aid facilitators in increasing their confidence with content and practices.

Teamwork is another structure we found in Quavers to Quadratics and Science Theatre that helps ease anxiety and support the facilitators. We see this through the intersection of the *Mutuality of Engagement* code and *Negotiated Experiences*. Working with more experienced facilitators not only increased new members' confidence in themselves, it also moved the new facilitators inwards in the community because they felt supported. Additionally, the bonding between facilitators that was evident during both Science Theatre's (as mentioned by Grace) and Quavers to Quadratics' (as mentioned by Orla) trips caused positive identity development and further shows how the interaction between members of these groups is important.

5.6 Summary

In summary, we have used the intersection of Community Dimensions and Mechanisms of Identity from the Communities of Practice framework to analyze three different informal physics programs. This application of the operationalized framework highlighted the opportunities for positive physics identity development among the student facilitators. Participating in informal programs supported their interest in physics, allowed them to be recognized as members of the physics community, and expanded and supported their participation in the practices of the physics community. From the coding, we identified some program structures that are key to moving members to more central positions in the informal physics communities of practice. These results are complementary to findings from previous studies that showed informal physics programs can provide growth opportunities for university physics students in specific physics practices - such as improved scientific communication skills [80] and pedagogical modalities [81, 82].

CHAPTER 6: FINDINGS FROM EXAMINING COP FORMATION IN AN ART AND PHYSICS INFORMAL PROGRAM

In previous work (Chapters 4 and 5), we have shown that some informal physics programs can act like a community of practice and that we can learn more about how facilitators are supported in these spaces through the use of the operationalized CoP framework. In this chapter, we switch to looking at a new informal physics program (that was established and implemented during the time of this study) and if and how it evolves into a community of practice. This new informal physics program not only focuses on physics concepts, but also brings graphic design elements into the program.

6.1 Introduction

Each physicist is a complex individual with many different interests both inside and outside of the field. When we go home for the day from school or work, we often have other interests and hobbies. Some physicists enjoy cooking, others enjoy traveling or being out in nature. Some physicists may enjoy playing a sport or engaging in creative hobbies. Personally, I identify as a competitive adult figure skater, a skating coach, and a figure skating judge among other things outside of my physics identity.

Physics has struggled to recognize the interests and identities of many of its members. Prior work has shown that physics identity development can lead to persistence within the field and other successes [20-21, 24, 33]. One place where a physics identity can develop are informal learning opportunities that allow for participants to become agents of their own learning and intersection with physics [29]. As described in Chapters 4 and 5, we have shown that some informal physics programs can support physics identities of its members by serving as communities of practice [71-72]. However, this prior work is focused on established informal physics programs, i.e. programs that have been running for at least five years, have robust volunteer support, and have clear organizational structures. As the physics community seeks to expand its informal education activities, insight is needed into how new informal physics programs are formed, and if and how they can become a community of practice that supports the multiple identities of its members.

Thus, in this chapter we examine the development of a new, specific informal physics learning project that was conceptualized and designed to be a community of practice. In particular, this project was deliberately designed to bring together physics and art, in order to create tools that would teach physics concepts in aesthetically pleasing ways. Over the summer of 2020, four undergraduate students (two majoring in physics who applied to be a part of the project and two majoring in graphic design who were invited to be involved), along with multiple faculty members, a physics postdoc, and a physics graduate student (myself) met frequently to create a website, called Bohring Art. The students chose the website name because they wanted it to be catchy and have a reference to both physics and art. They even decided to include a short section about Neils Bohr and how he contributed to the field.

This project provided a unique opportunity for us to examine the formation of a community of practice and the impacts it has on identity development within a project that consciously combines physics with other areas of interest.

Here we consider the following research questions: *To what extent did a community of practice form throughout the duration of the Bohring Art project? What impact did this interdisciplinary experience have on project participants' identity development?* To answer these questions, we followed the project from design through implementation, looking for markers of community of practice. Our approach was qualitative and utilized multiple data sources, including observations, participant reflections, interviews with participants, and collection of project artifacts.

6.2 Methodology

In this paper we are examining an entire informal physics project from the conception and planning phase to the implementation of having university students work together to create a public engagement tool. Data about the planning phase of this project comes from interviews conducted after the conclusion of the project with the co-developers (the physics postdoc and graphic design faculty member) and from observations of planning and application review meetings. The interviews asked the co-developers about their motivations and intentions for the project. Additionally, the researcher attended meetings in which the co-developers planned out what the four undergraduate students would do over the summer and when the applications were read for the undergraduate students.

In order to examine how a community of practice emerged within the project, we looked at 8 interviews (four students with two interviews each), a set of 36 written reflections (four students with nine reflections each), the 2 interviews conducted with the lead facilitators, and frequent observations of project meetings. Each student was interviewed once at the beginning and once at the near end of the 10-week project for about 30 minutes. The first interview focused on prior experience and expectations for the project while the second interview captured the experiences of each student within the summer project. Starting during the second week of the project, program facilitators asked each student to write and submit a short reflection each Friday. Each week there were unique prompts, such as “Can you describe in your own words what it means to do 'physics research' and to 'design' for some project (example: infographics)?” and “What was the hardest thing for you personally about working in this group? Was the group the right size for the task, or would it have been better larger/smaller?"

The operationalized Communities of Practice framework for informal physics programs was used to analyze the data. More specifically, we used the Community Dimension constructs (Accountability to the Enterprise, Mutuality of Engagement, and Negotiation of the Repertoire) in order to look at how members of the community experienced the project. In this work, we are looking for community formation (since this is a newer informal project) which would come through the Community Dimensions as opposed to the nuances of the experience that could come through the Mechanisms of Identity.

To code the data sets, the research team utilized MaxQDA software. Two members of the research team were responsible for coding the data. One researcher (myself) was involved in the operationalization process for the constructs being used and the other researcher was introduced to the framework as coding of this data started. To train the second researcher, we used a previously coded interview as an example of qualitative data that has been coded with the constructs (one of the interviews from the study in Chapter 5). Because the outside interview was coded, discussed, and validated by five researchers, we are confident that it provides a good example of the operationalized framework. Once the second researcher became familiar with all three constructs, both researchers selected and coded an interview from the current data set. Both researchers discussed the coding with each other and all differences were resolved. The second interview from that student was also coded and discussed. The remaining interviews and reflections were coded by one of the researchers and read over by the other researcher with any discrepancies resolved.

During the coding process we felt as though some important ideas were not being fully captured with our set of three Community Dimensions due to the unique nature of this project sitting at the intersection of physics and graphic design. This led to the creation of emergent codes: use/adoption of new practices, physics and art crossover, and challenges and suggestions. The first two of these codes were concerned with what new, shared practices unique to this project the students used. For example, students spoke in interviews about how exploring research on science communication influenced their work. The physics and art crossover code was used to capture instances where the students discussed the relationship between physics and art. For example, two of the students mentioned in written reflections that they were surprised to find similarities between the two fields of physics and art. Table 4 contains a description of each emergent code and examples from the data.

We would like to note the identities of the two researchers who collected and coded this data set. One researcher who has experience with the CoP framework is a white, female graduate (myself) student. She collected the data and also worked with the other researcher to code and analyze all of the data. The second researcher is a Black, male undergraduate student. Each researcher participated in the Physics/Art project, either as a graduate researcher or as an undergraduate physics student, and continued to work on the research aspects of this project after the conclusion of the summer. The involvement that both researchers had with the project over the summer provided unique insight to the data.

Table 4: Descriptions and examples of the emergent codes that were developed throughout the coding process.

Code	Summary	Example
Physics and Art Crossover	This code helps highlight important times when students seem to make meaningful connections between concepts of both physics and art. It was created to address a gray area of coding between the Negotiability of	"As the weeks progress, you will start to see the relationship between art and physics is more common than you think. There is plenty of art in physics"

	the Repertoire code and the Nexus of Multimembership code.	-art student
Challenges and Suggestions	This code covers more gray areas in the Negotiation of the Repertoire code, and addresses times when students talk about what practices of the CoP they liked, or what could have been better. It also focuses on times when students recall a challenging task that may have affected their experiences.	"I think a little more guidance at the beginning could be more helpful. We were a little lost at the beginning of where to start." -art student "If there was a similar project like this next summer, I would recommend getting input from a programmer earlier in the process because I think that can help with design." -physics student
Use/Adoption of Practices	This code was created to address times when students use (or claim they will use) a practice or idea from the opposite field of study (physics vs art). It highlights times that students may start to identify more with the other field or start to understand it. It bridges the gray area between the Negotiation of the Repertoire code and the Nexus of Multi Membership code.	"Definitely from now on, I'll definitely always consider art whenever I'm making the new exhibit, for example, for the planetarium or just making a new show at the planetarium." - physics student

6.3 Design of the Community of Practice (Planning Phase)

This project was first conceptualized by a physics postdoctoral researcher working with a physics education research group at an R1 university. She had previously collaborated with a community art space to create physics and art events and wanted to work with undergraduate students in this physics and art space. She responded to a call for community contribution to a science and art exhibit at a local museum that aims to combine art, science, design, and technology. When her proposal was accepted by the museum partner, she was auditing a graphic design class and asked the graphic design faculty member if she wanted to become involved. Together, the physics postdoc and the graphic design faculty member worked with the museum partner to lay out the project and identify undergraduate students who would work on the project (indicated on the far left of Figure 21). When ask about about the motivation for this project, the physics postdoc said:

> *So I always felt like there is this great opportunity in graphic design, especially interactive design, because it all talks about how you could communicate something with someone in a new, different way. . . . But then I felt like these two different things can get combined, but honestly, it was a huge gap that needed to be bridged. . . . So I think that was the starting point for bringing in people from both groups. But then after we got the money from [the museum partner], we figured, 'Okay. That is a great opportunity now to bring in students together from both disciplines so that they can work together.'*

Together, they planned to have a team of four paid undergraduate students (two of which were graphic design students who were invited to participate and two physics students who were chosen out of a pool of applicants). The physics postdoc and graphic design faculty were the main advisors for the undergraduate students and a physics graduate student also attended many project meetings, gave feedback to the students, and carried out all of the data collection activities for this research. Additionally two other physics faculty at the same institution were also tangentially involved and gave support to the three faculty/staff during the project formation process and to the students through infrequent meetings where the students presented on their progress. This group of people were the community of the Bohring Art CoP.

The program was intentionally designed to have the undergraduate students create a portion of an exhibit (interactive or non-interactive) that would convey physics concepts to a more general audience of non-physicists (the domain). Their portion of the exhibit was originally supposed to be a physical object located within the exhibit, however the COVID-19 pandemic required the students to consider a virtual contribution. Due to strict social distancing protocols, the entire team collaborated remotely and the students were given the agency to make all of the content and design decisions. The final product became the Bohring Art website, which was created by the undergraduate students to cater toward both science and non-science oriented persons, as it presents fun activities with delightful aesthetics that focus on introductory physics topics. Throughout the summer, the four students met daily via Zoom throughout the work week to discuss physics concepts and planning out activity designs (the practices).

6.4 Development of the Community of Practice

After the physics postdoc, graphic design faculty member, and museum partner conceptualized the project, the Bohring Art team started to grow and embark on the bulk of the work. During the summer, there were many new members of the project team and the community of practice started to form. Figure 21 shows three snapshots of the Bohring Art team and where each member of the project is positioned. The largest changes that took place between early and late summer are that the undergraduate students become central to the community of practice while the museum partner was no longer involved with the community of practice. After the funding was secured, the team at the museum partner institute provided minimal feedback to guide both the students and faculty toward a result that would fit with the style and narrative of the exhibit. The representatives from the museum partner were excited about the ideas for bohringart.com and left it up to the team to complete the work. This work was led by the four undergraduate students who did all of the website development work with frequent feedback from other members of the team. The following subsections describe how the four undergraduate students experienced the formation of the Community of Practice.

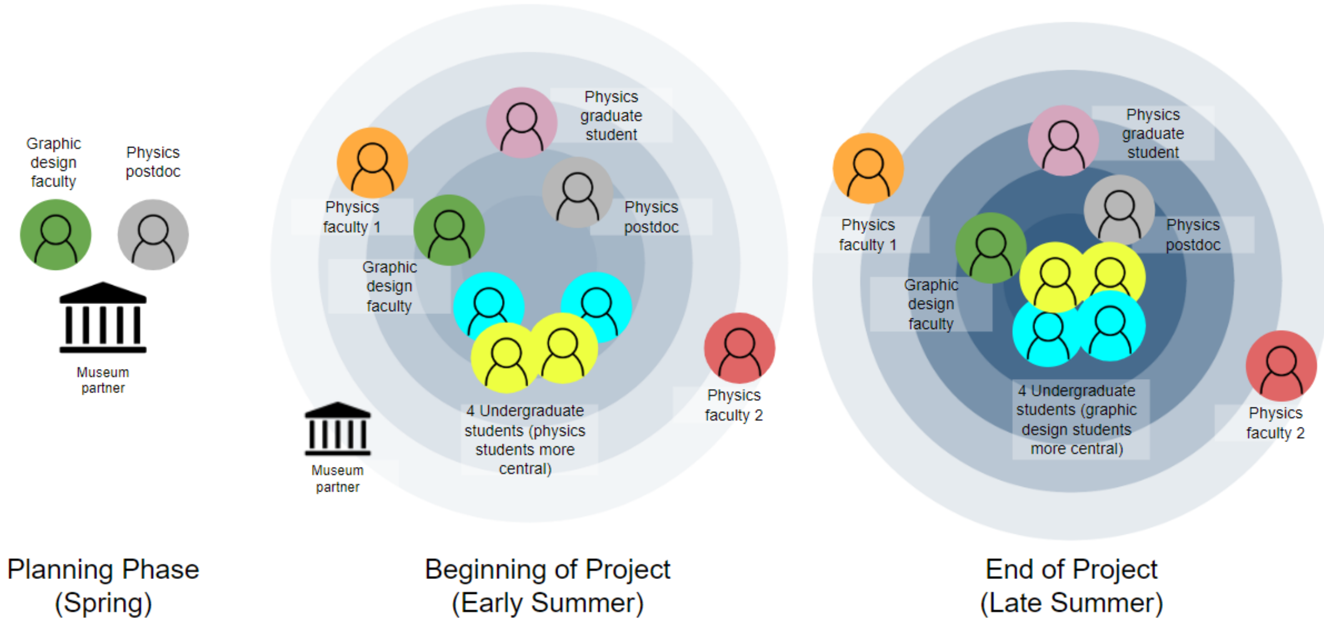


Figure 21: Visualization of three phases of the project (from left to right): 1) Planning Phase - the graphic design faculty member and the physics post-doc met with the community partner to intentionally design the experience for the students. 2) Beginning of Project - individual's initial roles and degrees of membership are indicated; this early stage of the community is signified by the lighter color background circles. 3) End of Project - the community of practice is more established with the students positioned centrally, the facilitators and supportive members positions more peripherally, and the absence of the museum partner.

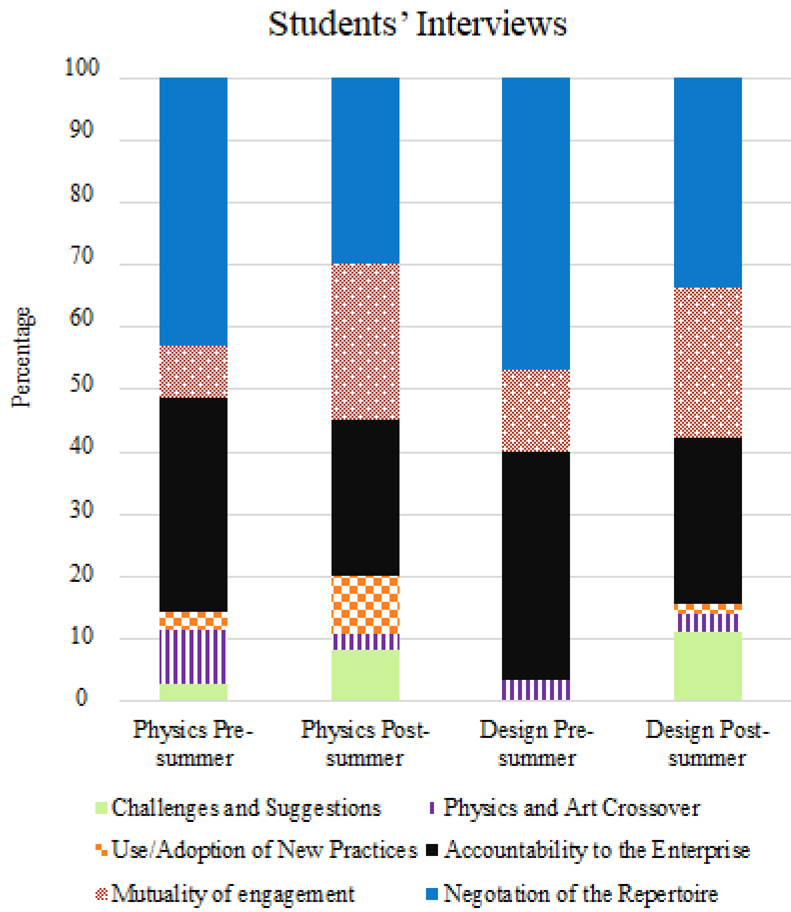


Figure 22: Percentage of the competence codes and the three emergent codes seen in all of the students' pre- and post- summer interviews (separated by physics and design students).

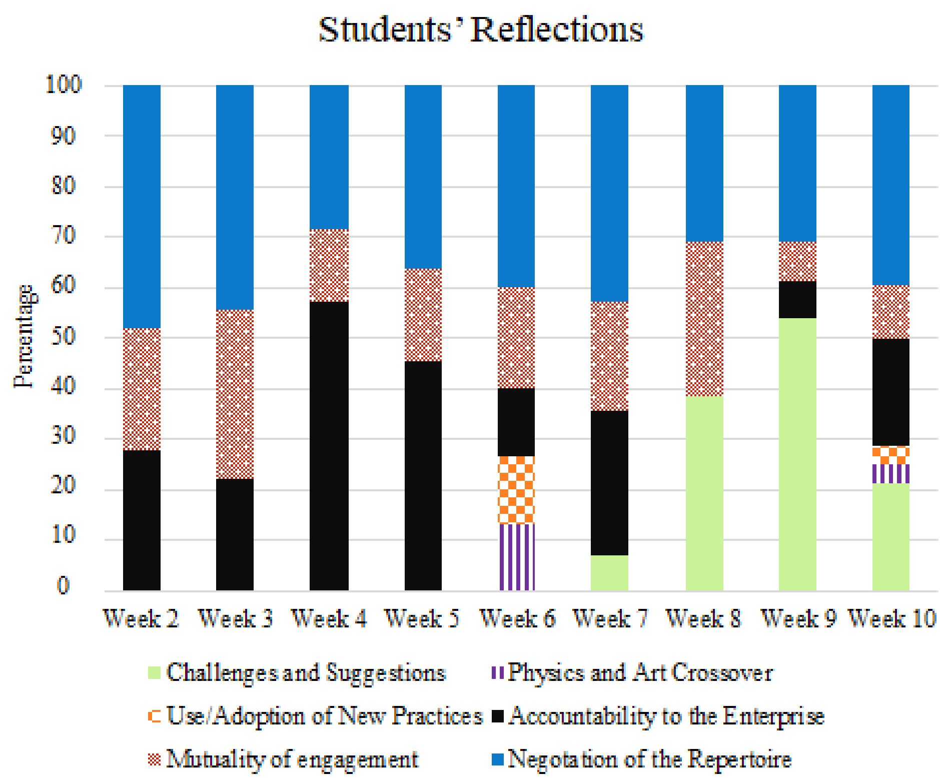


Figure 23: Overview of the codes seen in the pre-summer interviews (conducted during the first week of the project) and the post-summer interviews (conducted during the tenth week). The data is disaggregated by the discipline.

6.4.1 Establishing the Domain

In this study, we apply the three competence codes from the Community of Practice framework to our data because we are interested in how the participants experienced and perceived the Bohring Art project as it developed. To understand if a CoP was forming, we tracked how the participants saw the enterprise and viewed their accountability to it. Throughout the timeline of this project, we saw each of the students grapple with the goals of the project and the eventual product of the Bohring Art website. Looking at the *Accountability to the Enterprise* codes, we find that students were initially interested in working on the project for personal reasons. For instance the graphic design students both mentioned gaining job experience through working on an interdisciplinary project. Both the physics students talked about looking specifically for paid physics experience to add to their resumes. Because of the different backgrounds of the participants and their reasons for embarking on the project, initially the group found it challenging to establish what the project goals and outcomes would be. As one design student explained:

> *It was tough at the beginning to figure out where to start off on the project because we were kind of the ones that were laying down the foundation for it.*

The initial design of the project was intended to give the students agency about the product that they created, but there was an intentional focus on combining physics and graphic design. During the first seven weeks, we saw the students continually talking among themselves about what the goals for the individual activities on the website should be and why. They also had to deal with the completely virtual nature of the project as a result of COVID restrictions. They decided to create a series of online physics activities that would interest and excite users about four separate physics concepts (circuits, the star cycle, lasers and lenses, and kinematics). All of the students felt strongly about creating a visually appealing physics website that would teach others about the topics that they chose to cover. One physics student described this motivation in their end of summer interview:

> *I think the [website visitors] will really like the website. . . . I kind of just want to put this science interest in them that'll make them go and want to learn more about it and see that, "Oh, this is really interesting." . . . So I hope that . . . it'll break the stereotypes off of a lot of science stuff where it's like there's no way that . . . you can make learning about this interesting.*

One of the graphic design students also described his feelings toward the final product:

I'm hoping [the website] reaches students outside of the science field. I think that's the most important thing. I think we want this project to become relatable to students outside the science field or just any field, not just art or science. Obviously, you want students to notice the website has a cool design appeal to it, or the components are designed a little better or more in-depth than another website that might have some of the similar activities. But really we wanted it to reach all students of our age and like something that they wanted to take on, something they wanted to actually just experience if they weren't into science.

This arrival at a set of goals for the website became the domain of the group.

6.4.2 Developing the Community

Simultaneously while figuring out the goals of the project, the students were also building relationships with each other. The two undergraduate graphic design students already knew each other from a class that they had both taken during the spring semester. However, the physics students did not know each other nor did they know the design students. During the first week of the project students decided that project communication should occur through daily Zoom meetings as well as discussion over Slack among each other and with other members of the community. While the students only worked on this project for 10 weeks, their decision to meet virtually with each other for four hours every Monday through Friday created an opportunity for them to work closer together than other structures would have allowed.

Through the *Mutuality of Engagement* codes, we found that all four of the students described the process of forming relationships with the other project participants in a positive way. All four students mentioned needing time to get to know all of the other community members, including working with more senior people such as the physics postdoc and the graphic design faculty member. The earlier project meetings were more business-like with the students only focusing on the task at hand. However, later project meetings would include time for off topic conversation about everyone's personal lives. Since the community members were dispersed around the country due to all of the meetings taking place virtually, these meetings also included others asking about current events happening in the local context of others. In the words of a design student:

> *I think we have a strong relationship. At first, when you start the project, there's definitely a lot of hesitation and you don't really know each other . . . but obviously, during the course of a 10 week period, you start to form a little bit of a friendship . . . because you're really meeting every day and . . . you're learning more about each other as you go on. Where they're from, what they're doing outside of this project. So, it's really cool.*

One of the physics students also pointed out that the relationship between everyone was important because it provided a space to be able to both critique and provide ideas about the project:

> *So well, of course, at first, we're all going to be really weird around each other as we just met. And we're supposed to be working on this project. . . And by relationship, I guess, I mean the comfort level, where you're not afraid to say, "No, I actually think that's wrong." Or you're not afraid to like, "What if we did blah, blah, blah?" and give your opinion.*

Another theme that came out of the *Mutuality of Engagement* coding was related to the difficulties of having to work on the Bohring Art project remotely. Due to social distancing measures related to COVID-19, the team only met virtually during the summer. Some students noted that it took longer to establish relationships with members of the team, particularly the facilitators who were less central to the group, because they had never met them in person and only saw them virtually a few times a week. One of the physics students also noted that teaching physics virtually was a challenge. In contrast, a design student mentioned how working with people outside of the field of design was very important to him which in turn created a sense of importance around this project. These interactions among the members of the group formed a sense of community.

6.4.3 Engaging in the Practices

In order to create the final product, the team of students had to use their physics and design skills. The team met daily to work on different aspects of the project, including pinpointing and learning about the physics topics they wanted to cover as well as developing a wireframe for the website. Through the *Negotiation of the Repertoire* code, we see that while the design students started the summer with minimal physics knowledge, by the end of the project they felt as though they had learned the concepts. As one of the design students put it:

> *And I think some of the highlights of the summer were kind of learning about the new, or not the new, but the topics that [the physics students] were teaching us and how we can incorporate them in a fun aspect.*

In contrast, the physics students both mentioned having minimal to no knowledge about design but only learned a small amount throughout the summer. The physics students mainly saw their role as teaching the design students so that the design students could then build the website. As one of the physics students put it at the end of the summer:

> *Because I know that I'm a physics student, so I'm supposed to be helping [the design students] with certain things that they're trying to design, and I'm supposed to be working with [the other physics student] to come up with a curriculum for the*

website. But at times, it just seems like there was no work for me to do, or nothing to contribute sometimes because a lot of it would just be designed.

Similarly, one of the graphic design students mentioned that they saw their job as taking the physics concept and making it more interactive:

[The physics students] gave us ideas for the activity and we tried to figure out how we could formulate it into more interactiveness and how to bring more design into it.

While members of the project were all working on the same product, there were different strengths brought to the team by different members. Both the physics and design students noted that there was an imbalance of skill sharing. While the physics students spent a lot of time teaching physics to the design students, there was no time built in for the design students to teach. In the words of one design student:

I wish there was some time designated to teach [the physics students] some basic design skills.

6.4.4 Emergent codes/other lessons learned

We decided to create some emergent codes during the coding process in order to capture participants' thoughts specific to the design of this project, which included a focus on both physics and art concepts. One of the most salient findings was how the students described their view of the relationship between art and physics. The physics and art crossover code was used to capture instances where the students discussed the relationship between physics and art. For example, two of the students mentioned in written reflections that they were surprised to find similarities between the two fields of physics and art. One physics student wrote:

One interesting discovery I made was that physics and art are more interconnected than I previously imagined. I realize that while the methodologies and requirements ... are very different, the tasks are really the same. Both physics and art try to capture the essence of the universe in some sort of way, whether it be via equations or drawings of objects.

This was the first time that a project like this had been attempted by the facilitators and so soliciting feedback and hearing about each student's challenges was very useful. The two weekly reflections later in the summer included prompts that were meant to elicit some of this feedback. The prompt for the eight week of the project was, "What was the hardest thing for you personally about working in this group? Was the group the right size for the task, or would it have been better larger/smaller?" and the prompt for the ninth week was, "If you were in charge of this project (ie you were in Dena's position), what are some of the things you might have changed about this summer? How might this project have looked different? If we did a similar project next summer, what recommendations do you have for making the summer a better experience?" Many students wrote in their weekly reflections that they felt the group size (four undergraduate students) was ideal and that they enjoyed having agency over choosing the physics topics that would be covered on the website. As two of the students wrote:

The group size is actually appropriate since there is enough dissent amongst the group to make it useful but small enough that it doesn't become a hassle. Not only that, but having 2 scientists and artists means we can assist each other with concepts and fill in for the other if a person has to leave for a day. Having 4 people was the best decision, and I figure our efficiency wouldn't have been better otherwise.

I think that our group size is the perfect amount. Having it just be four people, we were able to build a better connection amongst each other. On top of that, it makes it easier to work together because you know what everyone is supposed to do. If it was a bigger team as in more physics and graphic design students, it would be harder to keep things more in control and there could be more clashing of design styles.

However, both the physics and design students noted that there was an imbalance of skill sharing. While the physics students spent a lot of time teaching physics to the design students, there was no time built in for the design students to teach. In the words of one design student:

I wish there was some time designated to teach [the physics students] some basic design skills.

Related, one of the physics students wrote:

If we did another project next summer, the only recommendation I would make is actually having formal lessons for physics and for art. While [the other physics student] and I do give formal lessons for the physics concepts, it would certainly be less risky if we also had [the physics postdocs] provide some lessons. Also, lessons about art from [the art faculty member] would be awesome!

The structure of this project intended for both design and physics to be equally discussed among the students. In the future, there may be a need for more structures in place to ensure that one field is treated as more important or given more time than another field. This quote highlights an important aspect of how program design is connected to experiences and the CoP formation -

providing space and structure in the design allowed for, but also limited, the development of different roles.

Overall, all of the students reflected positively on the summer experience during their tenth and final weekly reflection prompt. Both of the graphic design students shared that their knowledge of physics had increased and that they gained design experience. They wrote:

> *I am very grateful to have had this experience to work with the physics student and merge both of our fields together to help teach physics. I was worried at first that I would not be able to get any type of design experience over the summer. Over the course of the summer, I have gained knowledge in three different physics topics. I would say that I am comfortable to talk about them at a beginner level. It has been many years since I had to actually sit down and think about physics. The topics we talked about were actually interesting.*

> *This summer project was a very rewarding experience. During the course of the 10 weeks we were able to accomplish a great deal of work. This experience has taught me some skills that I can now add to my resume and be able to use in an actual business atmosphere. Having designed a website will be a great piece to add to my portfolio and to show to future employers.*

Both of the physics students also shared that they had a positive experience and both pointed out that the project provided them with experience teaching others about physics. In their own words:

> *I truly enjoyed the time spent working on the project. I accomplished a good amount of work: coming up with three unique ideas for teaching physics, actually teaching physics to two art students (something I never really do), and helping lead the*

group. It was also enjoyable to just have random chats with everyone, joke around sometimes, and learn about graphic design and better approaches to teaching.

I think we have created a website that the user will appreciate, and they will be able to tell that a lot of thought was put into it. Over the summer I have learned much more about physics and have refined the knowledge that I already had. I also learned a lot about the process of design through watching Wyatt and Danny and noticing the way they made design decisions based on necessity and the overall website theme/narrative.

6.5 Discussion

In contrast to prior work that looked at CoPs within well established informal physics programs, this paper is a first step at looking at how communities of practice might form within a newer or developing informal physics space. We used the operationalized Community of Practice framework to understand the formation of the CoP in the Bohring art project. The main takeaway is that the co-developers had intentional designs around CoP but the actual domain and practices as well as the communication between community members were negotiated by members over time. Interesting findings include the shift in the role of the museum partner from contributing to the project design to no longer being involved in the CoP. We also found that a CoP formed even though the project was forced to be virtual, partly due to the frequency of meetings and structures for communication. We saw that the physics students did more teaching and less learning than the graphic design students, resulting in them being more central during the content development and less central during the final stages of graphic design. These results lead to some implications for future projects including being mindful of how much physics content experts are contributing and learning from others and what role community partners should play within the program.

CHAPTER 7: CONCLUSION

In this work, I set out to use the Communities of Practice framework in order to better understand how both facilitators and participants in informal physics programs are impacted by that experience. After determining that some informal physics programs can be characterized as a community of practice, I operationalized the framework so that it would be contextualized to the informal physics space (described in chapter 4). This operationalization of the framework was done with a team of researchers who iteratively revised a codebook by analyzing a subset of interviews from informal physics program facilitators. The final coding scheme contained two main parts: the Community Dimensions and the Mechanisms of Identity. Each of these two parts helps us understand different parts of the informal physics program experience among individual facilitators or participants as well as the program as a whole. Then, I applied the operationalized Community of Practice framework to data from three distinct informal physics programs (described in chapter 5) to understand how the different structures of these programs can support physics identity development. Finally, thinking about spaces that incorporate both physics and other ideas, I applied the framework to data from participants and facilitators from a physics and graphic design project that went through various stages of being a community of practice.

I started off this dissertation by describing the main goal for this collection of work was to use the Communities of Practice framework to understand the experiences that facilitators or participants have within informal physis spaces. This larger overarching goal is seen through the studies, but smaller scope research questions guided each study. I summarize the outcomes seen for each of those research questions below.

Can an informal physics program function as a community of practice? There are three essential elements that need to be identified in order for a group to be considered a community of practice: the domain (a common goal or idea that the group cares about), the community (a well defined group of people who are members of the community), and practices (a set of ways of going about working toward the common goal). While there is a wide range of informal physics programs and how they can be structured, we are able to identify a domain, community, and practice within each of the four informal physics programs examined in this work (PISEC, Science Theatre, Quavers to Quadratics, and Bohring Art). This leads us to believe that the Communities of Practice framework is appropriate for examining the experiences within these spaces.

Can we operationalize the Communities of Practice framework to help us establish membership (and therefore identity) within the community of practice? By using an iterative process with interviews from facilitators in informal physics programs, we were able to operationalize the Communities of Practice framework so that each construct is defined within the context of informal physics programs. The operationalized framework allows us to understand how participation in informal physics programs may impact university physics students' identity and sense of belonging within the physics field. The power of this framework is that it allows us to sense where the university students see themselves within the Community of Practice and to learn what aspects of that community impact their involvement. From the point of view of physics identity, this is important because we can understand how participation in informal programs allows for the growth of a physics identity and how these students can become more central members within the physics community.

What structures and/or mechanisms within an informal physics community foster (or hinder) membership and identity development? This application of the operationalized CoP framework to three informal physics programs highlighted the opportunities for positive physics identity development among the student facilitators. Participating in informal programs supported their interest in physics, allowed them to be recognized as members of the physics community, and expanded and supported their participation in the practices of the physics community. From the coding, we identified the following aspects of an informal physics program that are important for identity development: a mission that aligns with facilitator values, flexible and thorough training, supportive schedules that allow facilitators with multiple commitments to participate, mentorship between more experienced facilitators and newer facilitators, and opportunities for interacting with the audience. These structures can help mitigate anxiety that newer facilitators may feel when starting in their role and fitting informal physics experiences into an already busy schedule.

To what extent did a community of practice form within a new physics and art informal program? We see that the Bohring Art project does not form a community of practice during the planning phase (where there were only three members present) but that a community of practice does emerge through the summer with the students defining their own goals for the website and creating their own practices to achieve those goals. We found that a CoP formed even though the project was forced to be virtual, partly due to the frequency of meetings and structures for communication. In terms of developing both physics and art identities, we saw that the physics students did more teaching about physics and less learning about graphic design whereas the graphic design students did more learning about physics than teaching graphic design concepts. This resulted in the physics students being more central during the content development and less central during the final stages of graphic design. These results lead to some considerations for future projects that aim for both fields of study to be equal. Practitioners may want to intentionally design activities so that physics and art (or any other subject area) are equally taught and learned among participants.

Major contributions: One contribution to the field from this dissertation is an operationalized framework that is useful for examining informal physics spaces. The codebook thoroughly defines the framework so that both researchers and practitioners can use it to examine informal programs. Our look at an informal physics program that also focused on graphic design shows that the CoP framework is versatile and can be used in a variety of informal contexts that have CoP structures. The analysis has led to a set of important structures that allow facilitators the opportunity to grow and nurture their physics identity. These structures are important for current and future practitioners that want to build an informal physics program that will not only benefit audience members, but also the facilitators within the program.

Limitations to this dissertation: As already mentioned, there are some limitations that need to be considered when thinking about the implications of this study. First, in this dissertation we looked closely at four informal programs which may have resulted in not capturing all relevant structures. Many informal education spaces have creative and innovative formats that we could look at in order to see if there are other structures that provide identity development support to facilitators. Another limitation comes when considering that the CoP framework might not apply to informal learning scenarios that are still relevant or important to learners. For example, some informal learning takes place through media (social media, popularized physics TV shows/documentaries, etc.).

In terms of the data analyzed in this dissertation, there are limitations on who's stories were shared. We are missing people who do not have a “good” or “successful” experience in the programs because participants self-selected to be involved in the studies. Another way of thinking about this is that we do not have the data for the peripheral members and peripheral members of informal physics groups could be more likely to be peripheral members of the physics community as well i.e. students of color, women, and others from marginalized groups. This means our work might not speak to the full range of experiences of students and miss negative experiences some might have. More work needs to be done to understand if and why people do not participate in these groups.

As the operationalized CoP framework simply requires an informal physics program to operate as a community of practice – a group of people working together (a community) to achieve a shared mission (a domain) through various activities (practices) - it can be used by practitioners to analyze their programs. I hope that this framework can serve as a valuable tool for both researchers and practitioners to further explore different types of informal physics programs and the ways in which programs can support student facilitators.

I also envision this operationalized framework being useful for many contexts outside of informal physics programs to analyze different aspects of physics identity development. There are many communities of practice in action in the daily life of a physicist. For example, the physics department of a university has a domain that includes furthering physics research and educating the physicists of the future, a community of physicists, and a practice involving giving lectures and running labs for students, conducting experiments and other research, participating in seminars and conferences etc. This framework could be used to analyze how members of that community of practice feel supported (or not) with the continuous development of their identity as a physicist.

Further, the framework can tweeze out structures and norms that can be crucial factors towards people moving more centrally in the community. Thus, physics departments may be able to use this information to make adjustments to foster more positive identity development for all of its members.

Informal physics programs are part of the physics community's practices. Involving physics students in public engagement with local communities is clearly something that is valuable not just to audiences but also to the physics students themselves. Through research and evaluation of these programs, including the use of a community of practice lenses, we will be better able to provide support for all participants who engage with physics outside of the classroom.

APPENDICES

APPENDIX A: INTERVIEW PROTOCOLS

Science Theatre Pre-trip Protocol

1. When did you first get involved with Science Theatre?
    a. How did you hear about it?
    b. What made you want to join?
2. What have you done with Science Theatre this year (or since you joined)?
    a. How has this level of involvement changed, if at all, from last year?
    b. Are you involved with shows? Trainings? Weekly meetings? Creating demos?
    c. What has your experience been like with other members of the group?
3. Can you tell me what participating in Science Theatre has meant to you?
    a. Why is it important to you?
4. Are you involved with any other outreach/informal programs as a volunteer? (prompt: Could have been in high school or college or another time in your life. These also could have been science or not science related.)
5. What are you looking to do after you graduate?
    a. [if not mentioned] Does this include graduate school?
    b. [if not mentioned] What sort of job would you like to have?
6. Do you identify as a scientist or a science-person?
7. Do you see your Science Theatre experience affecting your future career? If yes, how so?
8. Do you think it is important for scientists to do outreach or work with the public? What about specifically in your discipline?
9. Have you had any past experiences with outreach/informal learning where you were the "audience"? Can you tell me what that was like?
    a. Was that experience important to you?
    b. When did that experience take place?
10. Why did you decide to go on the Upper Peninsula Spring Break trip?
11. What are your expectations heading into the trip?
    a. Is there anything you are looking forward to?
    b. Is there anything you are nervous about?

Science Theatre Post-trip Protocol

1. Overall, how was the trip?
2. Can you describe a typical day?
    a. How many shows did you do?
    b. How was the driving?
    c. Where did you stay?
    d. What did you do when you were not visiting schools?
3. What was the most challenging thing about being on the trip?
4. What was the most fun thing about being on the trip?
5. What was the most surprising thing about being on the trip?

    Prompts if they cannot think of anything:
    a. Working with other Science Theatre members

b. Number of shows
c. The schools that were visited
d. Rural places in the upper peninsula
e. The students
f. Driving and staying overnight in different towns
g. The demos that were used

6. What demos did you do? Can you tell me a couple that you liked the most or did the most?
7. Had you done those demos before going on the trip?
8. For any of the demos, did you bring in or use any knowledge from your background or major?
9. Did you have to troubleshoot any demos while on the trip?
    a. If yes, how did you handle that situation?
10. What kinds of questions did you ask the audience in the presentation of the demos? What is your strategy for asking questions and getting responses?
11. How did you consider different audience ages in your presentation? Can you give me an example from the trip?
12. What is your style/strategy in presenting demos to the audience?
    a. What do you wear?
    b. What vocal tone or inflection do you use?
    c. Do you use facial expressions, body language, or gestures during your presentations?
    d. Do you call on audience members?
    e. Are there other things you do?
13. What was the audience reaction to your presentation? Did that differ with different audiences?
14. What do you think the impact of the presentation is on the audience?
15. How do you think doing the demos in front of the audience affects their understanding of the science content?
16. Would you go on the trip again? Why?
17. What was the impact of the trip on you?
18. Did the trip have any impact on how you think about outreach or education?
19. Will you be involved with Science Theatre in the future?
20. Is there anything else that you feel like you might want to share that we have not talked about yet?

Quavers to Quadratics Pre-Galway Trip Protocol

1. Can you tell me your name, degree and year in college please?
2. Tell me about any previous experience with Q2Q you have.
    a. When did you first participate?
    b. What made you want to join?
3. What were your motivations to participate in the Galway edition of Q2Q?
4. How are you feeling about the trip?
    a. [if they have previous experience with Q2Q] Do you think it will be different to your previous experiences with Q2Q? Why?

5. In this trip some of the workshops are done through Irish. How do you feel about that?
    a. How would you describe your level of Irish?
    b. How does Irish interact with your everyday life?
6. Can you describe your relationship with your fellow facilitators?
    a. Do you interact with them much outside of Q2Q?
    b. Do you think going on this trip together will change those relationships much?
    c. How do you feel about spending a week together?
7. Part of this trip is helping to train your counterparts in Galway adding another layer to your role. How do you feel about that?
    a. Do you feel experienced enough to train others?

Quavers to Quadratics Post-Galway Trip Protocol

1. How was the trip? What were the major highlights?
2. Did everything go as you expected? Any surprises?
3. How do you feel about the trip now? Would you do it again?
4. How did it compare to your previous Q2Q experiences?
    a. How were the children, the facilities, the other facilitators?
5. How did the Irish workshops go?
    a. Was it harder/easier than you expected?
    b. How did the children react to your level of Irish?
    c. How did that affect your confidence as a facilitator?
6. How would you describe your relationship with your fellow facilitators now?
    a. How did the trip affect this?
    b. Do you feel more a part of Q2Q because of this?
7. How did your Galway counterparts react to Q2Q?
    a. Did you see any connections between how they felt and how you felt when you first started Q2Q?
    b. Did you give them much advice? If so, what was it?

PISEC Interview Protocol

1. Why did you decide to volunteer with the PISEC program?
    a. What semesters did you volunteer and what schools were you at?
    b. Why did you volunteer again this semester?
    c. Did you have any hesitations on volunteering? If yes, what were they?
    d. Are there reasons you would not volunteer in the future?
2. Were there things you didn't expect to happen that did throughout your experiences within PISEC?
    a. Can you give an example?
3. Were there any kids you connected with most?
    a. Why?
4. Do you feel like you are making an impact on the kids in your group?
    a. How? /What kind?
    b. Can you give an example?

5. Have your kids impacted you?
    a. How?
    b. Tell me more
6. Do you think the kids you worked with will end up doing science in the future?
    a. Why ?
    b. Are there a few/one kid that comes to mind?
7. Do you see similarities/differences between your childhood and the kids who participate in PISEC?
    a. Can you give an example?
8. Have you ever participated in any informal science programs outside of the outreach program in your past or currently?
    a. How about any other type of outreach?
    b. What programs?
    c. In what ways has participating in these programs benefited you?
9. What have you gained from those experiences?
    a. What is the most important thing you got out of them?
10. How have they played a role in you becoming a physicist?
    a. Could you see yourself in the field of physics without participating/having participated in these programs?
11. Have you ever participated in any arts or performing arts?
    a. How/have they played a role in you becoming a physicist?

Bohring Art Beginning of Summer Student Protocol

1. Hi, can you tell me your name, major, your year and where you are from?
2. Tell me about your physics experience. Did you take physics in high school? How do you engage with physics now?
3. Do you identify as a scientist? Or as a science-person?
4. Tell me about your creative experiences. Have you taken any creative courses? How do you engage with creative work now?
5. Do you identify as an artistic or creative person?
6. Tell me about any previous experience you have with projects that combine different areas of study like art and science.
7. What were your motivations to participate in this summer project with the Science Gallery Detroit?
    a. How did you hear about it?
    b. What are your expectations heading into the summer?
8. How are you feeling about the summer?
    a. Are you worried about any aspects of the summer?
    b. What are you most excited about?
    c. What are you hoping to create?
9. What are you looking to do after you graduate? (Job? Grad school? Other?)
    a. Has this changed recently? Or evolved over the time you have been in school?
10. Do you see your summer experience with this project experience affecting your future career?

11. Have you had any past experiences with outreach/informal where you were the "audience"? Can you tell me what that was like? (was it important to them? As a kid/adult audience? Or as a volunteer?) (omit if this interview is getting really long)
    a. Do you think these experiences will impact how you go about this summer project?
12. Do you think it is important for scientists to do outreach or work with the public? (specifically in physics?)

Bohring Art End of Summer Student Protocol

1. Overall, how was the summer/experience? What were the major highlights?
2. Did everything go as you expected? Any surprises?
3. Can you describe a typical week?
    a. What meetings did you have?
4. What was the most challenging thing about this project?
    a. If you go back in time, would you do anything differently?
    b. If you were to do a similar project in the future or continue for the fall, what are some of the skills/experiences you learned this summer that will help you overcome some of those challenges?
5. Would you engage with a similar project like this in the future? Why or why not?
6. What was the most fun thing about being in this project?
7. What was the most surprising thing about this project?
    a. Working with other team members?
    b. Virtual setting?
    c. Content?
    d. The product?
8. Who was involved with this project?
    a. Were there certain opinions that you valued?
    b. Did you talk to anyone about this project who was not on the project team?
9. How would you describe your relationship with your fellow teammates now?
    a. (Has this changed over time?)
    b. How did the project/summer affect this?
    c. Do you feel more a part of the science/design community because of this?
10. What tasks did you do? Can you tell me a little about the ones you liked the most or you did the most?
    a. For any of the tasks did you bring in or use any knowledge from your background or major?
11. When stuff didn't go right, what did you do?
    a. What did other people on the team do?
12. What do you think the impact of the website will be on visitors? What do you think they will get from it?
13. What was the impact of the project on you?
    a. Did the project have any impact on how you think about outreach or education?
    b. Did your view of physics or graphic design/art change over time?
14. If you were in charge of this project (ie you were in Dena's role or a part of the Science Gallery leadership), is there anything you'd do differently?

    a. How do you feel about your science/design communication skills?
    b. Were the resources you were exposed to during this project helpful for you in any way?
    c. Are there things you would improve/change if you were the supervisor?
15. Is there anything else that you feel like you might want to share that we have not talked about yet?
16. When you saw the job advert at the beginning you had some ideas about what this project is about. How was your real experience different from your initial expectations?
17. Has your perception of what physics, art, or design consists of changed during this project?

Bohring Art Facilitator Interview Protocol

1. When did you get involved with the Science Gallery project and what was your motivation?
    a. What inspired you to start this project? What was that process like?
2. How would you describe your role within the program?
    a. How do you define your relationship with the rest of the team?
    b. Are there any other details in that regard you would like to share with us here?
3. How has the partnership with the Science Gallery Detroit impacted the culture of the program?
    a. What other resources are available to the program, provided by the institution/physics dept/physics community at your institution, such as educational, structural (space, transportation) or personnel?
    b. How have your partners or funding sources impacted the program goals and content? Audiences reached?
4. You had to hold this program in a virtual space. How did that work out? How do you envision it being different if we had been in person?
5. Can you describe the team that made this program run? Who is involved and what do they do?
    a. Do the personnel receive training for the role they play in the program? What kind of training? For how long?
6. Can you describe the demographics of the program participants? Do you have any specific target demographics in mind when selecting the undergraduate students? What about when making the website?
7. Can you describe the physics contents/concepts that your program aims to cover? Has the content changed over time?
8. I am particularly interested in why you are blending art/design and physics. Can you speak to why this approach was chosen for this program and for these ages?
    a. How do you support developing excitement about both physics and art?
    b. Are you able to explore any of your personal interests during the program?
9. Can you describe the percentage of physics versus the percentage of art/design in this program?
10. What were the logistics of the program? What did you have to do each week to make things run smoothly?

11. In your own words, what do you think is the impact of your program on participants? (both the undergraduate students and the audience)
12. What makes the program successful? (is it a measurement of goals accomplishments, of outcomes, output, numbers)
    a. What are the characteristics of the program that makes it successful? Why?
13. Do you find that the students achieved their own goals? How did you help them achieve their goals? Were your own goals achieved?
14. Was the program designed with a particular framework or model in mind? What concepts were pulled from that framework during the design process? Has the program evolved to have different design elements?
15. What design elements/framework did you draw upon to help guide the students?
16. Can you describe what the word "diversity" means to you?
17. How do you see the mission of the program being carried out?
    a. If there is any focus on certain, marginalized voices: Do you think the mission is successful in reaching minority groups?
18. I am interested in how you are thinking about "the face of physics" during this program especially because we know that physics is currently facing issues of equity in regards to gender and race. I'm wondering what sort of thought is put into the identities of the student creators?
    a. What ways might you think about these issues in the future? Would you change selection processes for students if you were to do this again?
19. Do you have anything explicit in your program for minority groups? Can you described those support systems (i.e. financial support for low income students)
20. Are there any current challenges the program is experiencing?
21. Where do you see the program going in the next 5 years?
22. Anything else that you would like to share?

APPENDIX B: OPERATIONALIZED COP CODEBOOK

Table 5: Complete Community Dimensions codebook.

Community Dimension	Definition	Subcode	Subcode Definition
Accountability to the Enterprise (AE)	The mission or goal of the community. It is a joint pursuit that creates responsibility and accountability. The members will work towards the higher goal together collectively. It includes interest in the goal of the community and sharing the values of the community. Describes the level of commitment and group involvement. Expresses the members' understanding of the objectives of the community.	**Insider**	The individual has completely understood the goals and values of the community. The individual is highly committed and is very involved in the community. They are often seen as practitioners or core members.
		Peripheral	The individual is not a full member yet. They have knowledge of the community but do not participate fully. Often applies to new members or first-timers.
		Inbound	The individual is actively looking to move into a more central membership or increase their involvement with the community. For example returning back to the community after a break. Becoming more familiar with the values and goals of the community.
		Neutral	It is not clear to the individual whether they are going to be a more central member of the community. The direction of their movement is unclear.
		Outbound	The individual has decided to move out of the community or to move to a less-committed position within the community. This could be due to a negative experience with the community or due to graduation or moving etc.
Mutuality of Engagement (ME)	Interactions an individual has with other members of the community, for example peers, audience members or directors/coordinators. It describes interactions with a certain member. It can also describe how the individual is recognised by other members in the community or bonding with peers.	**Insider**	The individual is interacting and spending time with their peers both at the scheduled activities of the community as well as outside of them. Individuals describe being good friends with other members and being a part of the group.
		Peripheral	The individual does not know any of the other facilitators before joining.
		Inbound	Being recognised by other members (applies especially to new members) by getting invited to group activities or positions within the community. Describes interactions with other members that allow the individual to move to a more central position within the community.
		Neutral	It is not clear to the individual whether they are going to be a more central member of the community. The direction of their movement is unclear. For example if an individual is describing a somewhat negative experience with another member, but does not specify if that interaction has actually caused the individual to

			move outwards of the community.
		Outbound	Describes negative experiences and interactions with other members that lead to the individual wanting to move outward of the community.
Negotiation of the Repertoire (NR)	Describes the practices of the community. The individual may describe their perception of the skills they may or may not have. This also includes describing the specific activities the community performs and presents to their audience.	**Insider**	The individual shows confidence of their ability to perform the practices of the community.
		Peripheral	The individual shows some knowledge of the skills and practices of the community but may not feel entirely confident in their own ability to perform them.
		Inbound	The individual describes instances where they have learned new skills or are starting to gain confidence in their abilities.
		Neutral	It is not clear if the individual feels confident about their skills or not. This can also be used when the individual is describing the practices of the community, without describing their own ability.
		Outbound	The individual describes their lack of confidence or knowledge of the practices of the community, that has a negative effect on their involvement.

Table 6: Complete Mechanisms of Identity codebook.

Mechanisms of Identity	**Definition**
Negotiated Experience (NE)	Refers to the process of making meaning of experiences through participation in the community. It is related to our interactions with other members of the community and how those interactions form or perceptions of how individuals do or do not see themselves as members of the CoP. We defined who we are by the way we experience ourselves through participation and how we reify ourselves. Related to recognition and an understanding of what is value. We know who everyone is and their roles, who is good at what. Engagement in practices gives us experience of participation and what communities pay attention to reify participants. It is a way of being in the community. Through experiences and interactions with others we defines what is value.
Learning Trajectory (LT)	Events that have taken place in the past or things that have been learned that resulted in the participant becoming a member of the community. Incorporates past identities and possible futures into making meaning of the present; i.e. experiences that have led them to participate in different forms in different CoPs. We define who we are by where we have been. Our past experiences lead us to negotiate present and future experiences that determine how we participate and engage in the CoP. That is that our experiences give us context to determine what things are (or not important), what we learn and what not. Participation in a community impacts an individual's identity only to the extent that the practice of the community incorporates that person's past and fits into a valued future.

	The learning trajectory influences what elements of participation are perceived as important and what are marginal. Because learning and identity are work in progress then our Learning Trajectories are always evolving and reshaping/calibrating how we approach and participate in the CoP. Past experiences do not have to be decades old, it can be relatively recent but that a particular experience shaped how you approached following activities.
Nexus of Multimembership (NM)	Negotiating being members of two or more communities and how their role serves as a bridge between those communities. Each individual is composed of multiple identities and how they negotiate membership to these different communities. We define who we are by the ways we reconcile our various forms of membership into one identity. We belong to many CoP, some in the past, some just as peripheral, others full member, all forms of participation contribute to our complete mesh of identities. Having this multimembership impacts our forms of participation and interactions that require coordination. Different ways of engaging in a practice reflects different forms of individuality and it requires a construction of identity that includes different meanings and forms of participation, finding ways to coexist in the different forms of membership. My little poem: The weaving of multimembership creates the texture of the fabric of our identity
Community Membership (CM)	The forms of competence developed and valued by participants in the community, such as: ways in which community members interact; perspectives and interpretations they share; use of a shared repertoire and resources, how we look at the world, how we relate to others, and what we know how to do and don't know. It is related to the forms of competences and performances valued and learned while participating in the community. The more central member of the community we become the more we are perceived as competent by other members and we feel competent and able to perform well in the practices of the community. Community Memberships contributes to becoming a more central member through fostering the competence constructs, because we know how to engage in the community because we understand the goals and are competent in the practices of the community to achieve the goal.
Relationship between Local and Global (RbLG)	Related to the sense of belonging. Individuals are constantly negotiating their local ways of belonging and how that fits to a broader spectrum of practices, styles, and discourses. Being a member of a local CoP is connected with being a member of the more universal community; for example, being part of a physics community in an institution and belonging to the community of physics at large. We define who we are by negotiating local ways of belonging to broader constellations and manifestation of styles and discourses. Each CoP creates a picture of the broader context in which its practice is located. Broader categories attract our attention because those are more publicly reified than local CoP in which we experience them as part of a lived identity. In our local CoP we engage in pursuing the enterprise but also figuring out how our engagement and participation fits in the broader scheme of things, fits the purpose of achieving the goals of the broader CoP.

APPENDIX C: SUPPLEMENTAL INFORMATION

Identifying elements of Community of Practice for programs in this study

The three informal physics programs presented in this work were chosen, in part, because of the authors' existing knowledge and involvement with the programs as practitioners. The dual roles of practitioner-researcher, which many members of the research team play, allow for practitioner knowledge to be used as a data source, help identify elements of the community of practice, and guide data collection from other sources. Due to the authors' association with these programs, we are able to take a practitioner research approach to this part of our study. A practitioner research approach is aimed at allowing practitioners to use their experience within the research process as a way to directly improve a practice (Meerabeau, 1995 and Shaw, 2005) [37-38]. Adopting a version of this methodology allowed us to gather data easily, have some insight on how the program is run, and apply our own knowledge to the data analysis [37]. Additionally, this practitioner and researcher duality held by many of the authors was beneficial to this study in that it allowed for us to focus on how this research can be used to better informal physics programs [38].

Our methods for collecting and analyzing the practitioner data are as follows: First, each member of the research team, who was associated with a program wrote a multi-page description of how the program functions. These documents were shared with and discussed among all members of the research team. Other members of the team used that information to identify the key components of a community of practice for each program. These components were then discussed among the research team and descriptions of the *domain*, *community*, and *practice* were refined for each program. Below we share summaries of the practitioner descriptions of each program.

The table below summarizes the three key components for a community of practice (domain, community, and practice) for each of the informal programs discussed in this paper.

Table 7: Summary of domain, community, and practices for Quavers to Quadratics, Science Theatre, and PISEC.

	Quavers to Quadratics	**Science Theatre**	**PISEC**
Domain	● Aims to help children play with ideas common to physics and music and to build positive attitudes toward those subjects ● Provides teaching experiences for undergraduate physics, science education, and music education students who facilitate the program.	● Mission statement: "[G]et children and adults excited about the wonders of science." through demo performances ● Supports university students in their interest to explore passion for science, outreach and teaching.	● Aims to encourage children to explore pathways to a STEM career by engaging in authentic physics practices to co-construct knowledge and interest ● Provides university students a physics outreach opportunity that allows them to participate in the community.
Community	● Undergraduate student facilitators, professional musicians, and classroom teachers, program leaders are students and academics from physics education and music education ● Funding and support comes from a national cultural institution (National Concert Hall).	● Undergraduate student volunteer facilitators have regular meetings and social events ● Officer system in place with 12 elected positions that take on more responsibility in the group.	● Youth, ages 8-17, particularly Latinx and low-income families ● Undergraduate and graduate physics students and staff volunteer their time as facilitators ● A paid director organizes the program and creates curricular materials.
Practices	● The children experience a day-long workshop at the National Concert Hall with two pre-workshop and one post-workshop school visits ● Pairs of facilitators and the class teacher co-teach play-based activities that explore links between music and physics during school visits ● In the day-long workshop there are 3 different sets of activities, each led by groups of 3 to 4 facilitators	● Facilitators lead scripted demonstration performances and hands on activities ● Facilitators build new demonstrations and repair/improve existing ones ● A traveling troupe of facilitators spend a week running science demonstration shows around rural Michigan, visiting as many schools as possible ● The group maintains an archive of all of the demos and scripts that have been developed	● Facilitators individually lead small groups of students weekly in an after school program ● Facilitators encourage children to explore sets of authentic, inquiry-driven, scientific activities ● The facilitators mentor the students to encourage them to engage with STEM content and practices

Interviews

For the study we conducted 46 interviews: 15 were from PISEC participants, 10 for Science Theatre (from a total of 5 students), and 27 for Quavers to Quadratics (from a total of 21 students). The interview protocols for each program were similar but did vary slightly in the questions. In the case of Science Theatre, some of the questions on the protocol were directed to expectations about the trip and preparations for it. Also, in Science Theatre there is a hierarchical organization for the volunteers and some of the subjects in the study brought it up so there were questions around that structural element of the program. In a similar way, some of the questions on the PISEC protocol were around the nature of PISEC being a recurring activity in which the facilitators meet with the children on a regular basis through a semester so we inquired as to whether this was an important aspect of their motivation for participation. In the case of Quavers to Quadratics, variations on the protocol were around the nature of the interdisciplinary aspect of the program, for example whether level of competence in both physics and music was something that impacted their participation and if so, in which ways.

Another difference between protocols is that in the cases where we had earlier and later interviews we adapted the original protocol to have the same/similar questions. The questions in the earlier interview were more centered around motivation, what had led them to want to do informal, expectations about their participation, their identification within their discipline, their perception of outreach within their discipline, and the challenges to pursue their career. The later interview was focused more on whether expectations were met, what was learned, the practices, experiences, and how their perception of their discipline and outreach had changed (or not) after participating. All of the Science Theatre facilitators were interviewed twice (once before and once after a spring break road trip). Some Quavers to Quadratics facilitators were interviewed only once, after participation in Quavers to Quadratics for a cycle while others were interviewed twice during different cycles. These were students who had participated in Quavers to Quadratics more than once before and we wanted to hear how their experiences had been during the different participations/cycles. Finally, facilitators in PISEC were only interviewed once after completing a semester in PISEC. Some of the participants in PISEC had just completed their first semester, while others had done PISEC more than once before. The questions if it was their first time focused on their motivations and expectations for participation and how those were met (or not), while if they had participated more than once we would focus on why they were recurrent participants, what kept them coming back.

The table below details the pseudonym, background degree, level of experience in the program and the number of interviews given by each participant in this study.

Table 8:Summary of domain, community, and practices for Quavers to Quadratics, Science Theatre, and PISEC.

Program	**Pseudonym**	**Degree (Degree Stage in years)**	**Experience in Program**	**No. of Interviews**
Science Theatre	Tom	Undergrad Physical Science (2)	2nd year (Elected program officer)	2
Science Theatre	Daisy	Undergrad Engineering (4)	4th year (Elected program officer)	2
Science Theatre	Liam	Undergrad Psychology (1)	1st year	2
Science Theatre	Grace	Undergrad Physics (1)	1st year	2

Science Theatre	Jacob	Undergrad Physics (1)	1st year	2
Quavers to Quadratics	Eoin	Undergrad Physics (3)	1st session (Dublin)	2
Quavers to Quadratics	Orla	Undergrad Maths & Science Ed. (2)	1st and 2nd sessions (Dublin and Galway)	4
Quavers to Quadratics	Ciara	Undergrad Music Ed. (1)	1st session (Dublin)	1
Quavers to Quadratics	Mary	Undergrad Physics (4)	2nd and 3rd sessions (Dublin and Galway)	2
Quavers to Quadratics	Emer	Undergrad Maths & Science Ed. (2)	2nd session (Dublin)	1
Quavers to Quadratics	Sean	Undergrad Physics (3)	1st session (Galway)	2
PISEC	Tyler	Graduate Physics (2)	2nd semester	1
PISEC	Ryan	Undergrad Physics (4)	1st semester	1
PISEC	Ville	Post-doctorate Physics (1)	1st semester	1
PISEC	Ava	Graduate Physics (1)	1st semester	1
PISEC	Evan	Graduate Physics (3)	2nd semester	1
PISEC	Lily	Graduate Physics (2)	3rd semester	1
PISEC	Levi	Graduate Physics (4)	6th semester	1

Coding process

Before coding started some basic rules were established, such as: a) There is no specific unit for the code size. We code the length of which it is related to the corresponding code, so it could be a couple of words or full paragraphs - if it is still telling the same story and connected to the same code; b) The interviewer's text is only included in the coded segment if it is necessary for context purposes; c) The codes within a set (*Community Dimensions* or *Mechanisms of Identity*) are orthogonal; i.e. a coded segment cannot be coded simultaneously with two codes from the same set; d) Each code set (*Community Dimension*s or *Mechanisms of Identity*) should be accompanied by one or more interest codes; e)The community codes can overlap, because those indicate in which community the story is happening but also which community(ies) it is affecting.

Statistical analysis methods

For the statistical analysis we conducted a within and between group analysis. The within group analysis allowed us to compare the structures within the programs that had the biggest impact on students' identity development. That is, we were able to understand which elements of the corresponding program (structure and design) had more impact on students' identity, in which way, and why. The between analysis allowed us to compare the structures across programs, therefore which model of program had the biggest impact on university students' discipline based identity development.

A. Within analysis – Comparing categories

We are looking to determine if there is something within the structure of the program that has an impact on participants' *Community Dimensions* and therefore levels of membership within the community of practice, as well as the *Mechanisms of Identity*. For example, we compare if there is a statistical difference between the distribution of pairs of the *Community Dimensions*, such as *Accountability to the Enterprise* vs *Mutuality of Engagement* for Quavers to Quadratics. In order to do this, we used a non-parametric test because the data sets we are using do not follow a normal distribution. Furthermore, given that our data distributions are not similar we also used mean ranks comparison. Therefore, in this study we used a *sign test* to compare the *Community Dimensions* and *Mechanisms of Identity* within programs.

A.1 Sign Test

The sign test is a non-parametric equivalent to the paired-sample t test to determine differences between paired observation of one group. It does not require a normal or symmetrical distribution. However, there are three assumptions that need to be fulfilled in order for the test to be valid. Assumption 1, the dependent variable must be ordinal or continuous, which in our case are the *Community Dimensions* or *Mechanisms of Identity* coding percentages. Assumption 2, the independent variable should be two categorical/nominal, so for example intervention 1 and intervention 2, which in our case corresponds to the two dimensions we would be comparing, for example AE vs NR. Assumption 3, observations for each participant should be independent, which in our case is satisfied by the fact that interviews happened independently.

B. Between Analysis – Comparing programs

In this case, we are comparing structures between the programs and their impact on participants' *Community Dimensions.* As with the within analysis we need to use a non-parametric test for non-normal distribution. In this case we have chosen to use the Mann-Whitney test.

B.1 Mann-Whitney Test

The Mann-Whitney test is equivalent to an independent-sample t-test, compares two independent groups (so we are able to tell where the difference is from the previous result). However, it allows you to compare two groups when the distribution of the groups is not normal.

It requires that the dependent variable be continuous or ordinal and the independent variable to have 2 categorical/nominal independent groups. In this case our dependent variables correspond to the percentage of codes for the *Community Dimensions* or *Mechanisms of Identity* and the independent variables are the programs themselves. Therefore, we are comparing how the distribution of the *Community Dimensions* (or *Mechanism of Identity*) differs between the pair of programs. Another of the required assumptions that the data needs to satisfy is that there is independence of observation, i.e. that there is no relationship between the subjects for each group. In our case, this is true because none of our participants is part of more than one of the programs. In our case, because we cannot assume that our distributions are similar, we are only comparing mean ranks (not medians).

Community dimension and identity mechanism analysis graphs

To understand the interactions between the *Mechanisms of Identity* and *Community Dimensions*, i.e. in which way the different mechanisms impact the *Community Dimensions* we looked at the intersection/overlapping of those set of codes within the informal program community. We used the MaxQDA function of complex coding query to identify sections of the interview transcripts in which codes for *Mechanisms of Identity* intersect with *Community Dimensions* codes when referring to experiences related to the particular informal program. When programming this coding query the program retrieves only segments in which all the codes listed are assigned to the segment. Then to make the graph we created a pseudo-scale by assigning numbers to the subcodes of the *Mechanisms of Identity* and *Community Dimension* codes (see figure below). For example, for the *Mechanisms of Identity* we have three subcodes for each of the mechanisms to indicate movement. We assigned a number to the subcode that would reflect the directionality of the movement; i.e. for *in* we assigned a count of +1 indicating that it is a move forward in the scale, *neutral* was assigned 0 because indicates no movement, and *out* was assigned -1 because indicates a movement back in the scale. For the *Community Dimensions* we followed a similar rule for the subcodes: *insider* = 2, *inbound* = 1, *neutral* = 0, *peripheral* = -1, and *outbound* = -2. We created a 3 x 5 matrix where the *Community Dimensions* are in the X axis and the *Mechanisms of Identity* are in the Y axis. Then the frequency of the intersection between the subcodes of *Community Dimensions* and *Mechanisms of Identity* would be the number in the matrix. See Figure A1 below for an example of a matrix. For the graphical representation (seen in figures 5-7) we used proportional shapes to indicate frequency in percentages of the intersections, meaning the larger the shapes, the more frequently such intersections of codes occur.

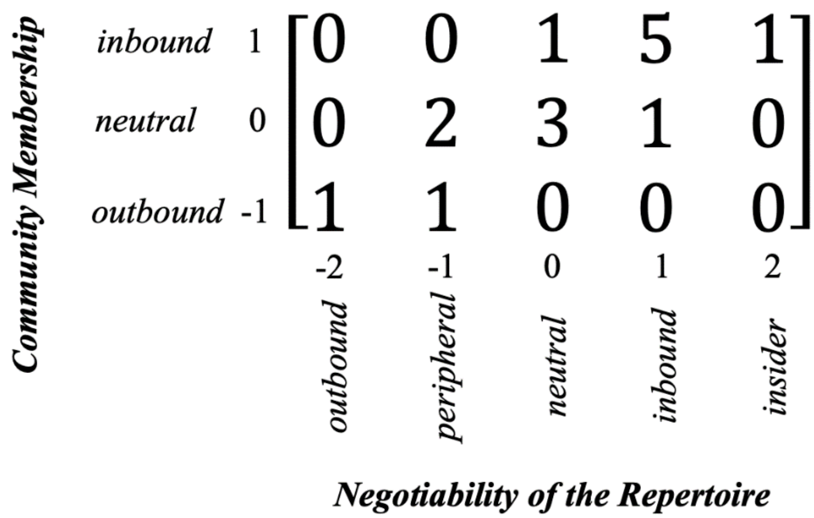


Figure 24: An example of how the matrix for the Community Dimensions and Mechanisms of Identity intersection graphs were created. This matrix shows how the Negotiability of the Repertoire subcodes, ranging from outbound = -2 to insider = 2, intersect the Community Membership subcodes, which range from outbound = -1 to inbound = 1.

Community Dimensions and Mechanisms of Identity interactions - further details

Nexus of Multimembership and *Accountability to the Enterprise:* For Quavers to Quadratics the interdisciplinary nature of the program allows facilitators to connect with their different interests and identities. This can be appreciated by the frequency of the *Nexus of Multimembership* mechanism (shown by the gray star) spread across the Quavers to Quadratics plot in Figure 4. Those who are physicists are excited about being able to connect their passion for physics and music, as everyone in the program has a music background of some form[1]. Quavers to Quadratics gives them the chance to reunite those aspects of their identity. At the same time, the facilitators who are science education majors are excited about having an opportunity to enact their roles as teachers, since many do not get that opportunity until later on in their career track. As mentioned by Orla:

> *It was very relevant to what I am studying because I am interested in education and also physics and I have experience in music from singing and doing shows and stuff growing up so yes it was really enjoyable had all those boxes ticked.*

This was coded *insider Accountability to the Enterprise* and *inbound Nexus of Multimembership* because of Orla's alignment with the Quavers to Quadratics mission and how her multiple identities were supported by her participation.

For PISEC, *Nexus of Multimembership* is the second most important mechanism interacting with *Accountability to the Enterprise* and has the interactions spreading across all quadrants. The main theme relates to balancing participation within multiple identities and interests as being a challenge for the facilitators. Tyler, when asked whether he had any hesitations

[1] The majority of facilitators in the program had to choose in high school to continue their studies in science or music and when the physicists chose studies in physics, they continued practicing music as a hobby.

about participating in PISEC, talks about wishing that he had more free time, saying “[I] can schedule stuff per week without feeling like I don't have time in lab.” The majority of the facilitators discussed in some form or another this tension about spending time doing PISEC versus working on their research. They go back and forth talking about how time not spent working in the lab may affect their participation in the physics research community of practice. For example, Tyler when asked whether the experiences of participating in PISEC and other outreach programs had impacted his role as a physicist he responds:

> *I think [the experiences in PISEC and other outreach activities] definitely, like, made me realize being, participating in some outreach all the time is a really good thing to do. Like, sort of whatever your level in physics, like, whether you're a grad student or a PI or, like, director of an institute, you always want to have a little outreach going on because it makes you- well, like, it's a nice break from your research. I'm definitely not less productive because I- Like, I don't think of less physics ideas because I take two hours out of my Tuesday afternoon to go volunteer. You know? It's just, like, physics is not based on, like, exactly how many hours you spend at your desk or in lab. I don't know, it makes me sort of happy and feeling like I'm helping the kids out.*

This reflection from Tyler was coded as *inbound Accountability to the Enterprise* and *inbound Nexus of Multimembership* because he is reconciling the idea that participation in the PISEC community of practice does not take away from his membership in the physics community. Furthermore, he is realizing that in fact it is something he values and would continue doing and committing to doing outreach.

In some cases, participation in PISEC helped the facilitators redefine their membership in the physics community, as Ava reflects when asked whether participation in PISEC had played a role in becoming a physicist or being a physicist:

> *[J]ust doing [PISEC] gave me like the confidence to be like I'm just going to do this whether or not my advisor supports it or not... in fact my advisor was kind of like not that supportive of doing outreach, because he was like 'yeah it's good but you should get your PhD first' kind of thing. So just doing it and like realizing that it was a good thing actually made me realize that maybe I need to be more confident about my opinions.*

Ava's growing commitment to PISEC indicated *inbound Accountability to the Enterprise* while the minor conflict between her and her PhD advisor about PISEC was coded with *neutral Nexus of Multimembership.* Participation in PISEC provided Ava with a space that allowed her to build confidence and realize how impactful her contribution to PISEC could be:

> *If I somehow influenced somebody, maybe it was like a ten year old girl that became like a genius of particle physics only because of this. And I think the fact that physics is so dominated by white males is just not sustainable. I mean, it's not optimal. It's not optimal, and so like I think it's in the end better for science to try to fix these issues.*

This shows that through her participation, Ava was allowed to reaffirm her commitment to PISEC (indicated through an *insider Accountability to the Enterprise* code*)* but also her participation in the physics community.

<u>*Learning Trajectory and Accountability to the Enterprise:*</u> In the case of Quavers to Quadratics, *Learning Trajectory* (shown by the green triangle in Figure 4) is the mechanism that

has an impact on initial participation on the program and is the second most coded mechanism interacting with *Accountability to the Enterprise*. The main themes that appear are related to either having or not having similar informal experiences during their youth and therefore wanting to provide such opportunities for children. As Seán, who also commented on his understanding of the domain of the physics community, narrates when asked why he wanted to join Quavers to Quadratics:

> *[I] just remember when I was taught how sound actually works [and] my mind was kind of blown in a way. Because I was like, 'ok this all makes perfect sense but I never really thought about it.' It's just something that you kind of that just happens to you. You don't think deeply about it at all so I think that is one thing that also excited me [about Quavers to Quadratics] was kind of showing people this is how sound works. Something you experience every day and it changes your perception of everyday life hopefully.*

This idea from Seán was coded as *insider Accountability to the Enterprise* and *inbound Learning Trajectory* because he is explaining how that experience put him in the trajectory to become a member of Quavers to Quadratics and work towards the community's mission - the interdisciplinary nature of the program.

Some facilitators' comments revealed how they actively look for informal programs when applying to university. This early thinking about joining an informal program is demonstrated by Tom when he says, "[I] knew entering university that Science Theatre was one of the big things that I wanted to do. And so I searched them out right away and started right away." This was coded as an *inbound* trajectory for *Accountability to the Enterprise* because it shows Tom interested in engaging in the community of practice and how he immediately worked toward becoming more accountable by joining the group. Furthermore, it was coded as *inbound Learning Trajectory* because Tom is explaining that he had learned about Science Theatre before coming to campus and had left a positive impression that he already knew he wanted to be part of the group. This perception of value and interest in participation in the informal physics community of practice was found in all three programs - of which two are based in the United States and one is based in Ireland - indicating an international consistency.

Community Membership and *Mutuality of Engagement:* The largest difference that we observe from Figure 6 is the interactions between *Mutuality of Engagement* and *Community Membership* for the Science Theatre program, which is not present in the other two programs. This could be related to the fact that *Community Membership* is related to the learning of skills and practices through interactions with other members, therefore aligning with the definition of *Mutuality of Engagement*. This is particularly true in Science Theatre in which the facilitators talked significantly about the different demos that they needed to learned and how initially they would just rely or emulate what more experienced facilitators would do until they were able to master them, this includes not only the content but also the way of communicating and engaging with the audience. This is supported by the main themes identified in the interactions between *Mutuality of Engagement* and *Community Membership* in Science Theatre, in which the facilitators talk about learning the practices of the program from a peer, as said by Liam: “But I'd love to be paired up with at least one or two officers. Because officers are cool and they know how to do everything. So if we're doing the angular momentum wheel I'll be like "can you please give me a crash course on how this works? Because I forgot all of it, and I don't know how to do it.” This segment was coded with *inbound Mutuality of Engagement* and *inbound Community Membership*.

Furthermore, Tom mentions the support from peers in the implementation of the practices: “generally, if someone feels a little uncomfortable and they're two of us that kind of know our stuff, we just double up on a demo.” This was coded as *neutral Mutuality of Engagement* and *inbound Community Membership* because Tom is talking about how the members within the community support each other as they gain confidence in the practices of the community. In the case of Quavers to Quadratics and PISEC, facilitators do not discuss as much how they support each other in the process of learning the practices and norms of the program. This could be in part based on the design of the programs. As mentioned before, PISEC facilitators received a one day training but they mostly work individually with the children and are there to support children’s creation. In the case of Quavers to Quadratics, facilitators are co-creators of the curriculum and practices of the program. They work together ahead of the workshops to discuss the activities and while newer members rely on experienced members, it seems that the co-creation element is not discussed much by facilitators. This is shown by the lack of *Community Membership* codes. This lack of discussion about a significant part of the Quavers to Quadratics practices warrants further investigation. It may have not been prompted during the interviews or facilitators may not value this aspect of the practices. The Quavers to Quadratics facilitators tended to focus more on their interactions with the children which were usually coded with the *Negotiated Experiences* identity mechanism.

Negotiated Experiences and *Negotiability of the Repertoire:* The second most frequent interaction across all three programs was with the *Negotiated Experiences* mechanism. In general, these interactions were related to two main themes: facilitators mentioning discussions with peers about competency in the practices, such as how to provide the best experiences for the children, and the cases of successful engagement they did have with them. In PISEC, we see Ava talking about her excitement with seeing the students grasp difficult concepts:

> *Yeah, so like, we had one day where we were doing the breadboard optics thing where they like slide, and they were trying to image stuff and, like, all of a sudden like, they got one image to work really well and like they were super excited about it, and actually all the kids in the other groups were, like, coming over and trying to see because it was really cool, and like that was pretty exciting. Because like that's a pretty actually sophisticated experiment, to like image things, and like that worked really well on the rails. I never got to do like, I didn't understand those concepts until I was like in grad school, so like yeah. That was fun.*

This was coded as *inbound Negotiability of the Repertoire* and *inbound Negotiated Experiences* because Ava is discussing one of the PISEC activities and how the children's engagement with that activity was motivating. She goes on to discuss how being part of PISEC has "improved her motivation and mood." However, there were interesting cases such as *inbound Negotiability of the Repertoire* interactions with *outbound Negotiated Experiences* where the facilitators were quite familiar with the practices enough to notice when one did not work out resulting in a more negative interaction with the audience.

The overlap between *Negotiated Experiences* and *Negotiability of the Enterprise* tended to show similar themes across all three programs. However, the way the *Learning Trajectory* and *Nexus of Multimembership* codes overlapped with *Negotiability of the Enterprise* showed how the different designs of Science Theatre and Quavers to Quadratics caused their facilitators to interact with the practices differently.

Learning Trajectory and Negotiability of the Repertoire: In Science Theatre, facilitators discuss extensively the performance aspect built into how the content is presented. This means that the performance practice is an important part of their membership and is connected to their confidence in performing the content, as expressed by Liam:

> *[A]t the start of the trip I was presenting. And I was presenting like-- I was presenting not like me. I was presenting it, but I was presenting it from how I remembered someone else doing it. And by the end of the trip, it was-- I had seen other people do it. I knew how other people did it. And yet, I was like, 'No. No. I want to add my flair to this.'*

This quote from Liam was coded as *Negotiability of the Repertoire* with a positive (*inbound*) movement because Liam discussed how as he engaged more in the practices of performing the demos he was able to bring some of his personal flair to it and connect with the audience. In this case, the *inbound Learning Trajectory* code was used as the practices of the program allows Liam to build his identity not just around the program but connecting elements of his other identities to the Science Theatre practices.

Comparably, Quavers to Quadratics is an interdisciplinary informal program, which requires children to play with ideas common to physics and music. Facilitators are tasked with co-creating those interdisciplinary practices, requiring the development of a repertoire distinct from that associated with their roles as "just" a physics or music student. Therefore, the learning and understanding of the content and practices of the program represent an important part of being a member of the community. In Mullen, et. al [4] we present how the interdisciplinary nature of the program helps facilitators navigate their multiple identities in physics and music. For example, Ciara, who is a music student and was interviewed during her first time participating in Quavers to Quadratics, talks about engaging in the practices of the program. She was really open about not knowing much physics but expressing that it was an enjoyable challenge for her and led her to spend time learning physics so she could teach it well. “I didn't study physics, but um, that was kind of like a factor that kind of excited me as a bit of a challenge to do something that I hadn't really much exposed before.” This quote was coded as *inbound Negotiability of the Repertoire* and *inbound Learning Trajectory* because Ciara is discussing how the fact that a big element of the repertoire of Quavers to Quadratics was the connection between music (which she identifies with as a music major) and physics (which she does not identify as having much knowledge of) was something that attracted her and prompted her participation, later supporting the development of a science identity as result of her participation in Quavers to Quadratics.

Nexus of Multimembership and *Negotiability of the Enterprise:* While Science Theatre and Quavers to Quadratics are similar in many ways, there are structural differences reflected within the portions of the interviews coded with the *insider* subcode of *Negotiability of the Repertoire*. Quavers to Quadratics facilitators have agency designing the activities and this level of agency had a considerable impact on facilitators’ perceived membership within the community, reflected through the larger percentage of *insider* quotes (39%, compared to 13% for Science Theatre. See Table in Figure 5 for details)[2]. This agency allows facilitators to reflect on the practices of the program and how these can be improved to support the mission of the community. Orla describes this when she says:

> *[T]he two things that we learned a lot from this week was to have more integration of music and science like I had kids in the seeing sound room as a “science room”. I hadn’t even thought about the fact that we should have more music in there*

[2] Also interesting to point out that there were no *insider Negotiability of the Repertoire* codes for PISEC. In PISEC, facilitators do not participate in the design of the curriculum or structure of the program’s practices.

> *because I thought, like, that is the science room then we have the music room and the creating room brings them together. But it actually is a lot more beneficial to have music and science in all of the rooms because then when you are asking the kids is there a link between the two then they can see it more and like you know yes that is better.*

Orla's increased understanding of how the practices in Quavers to Quadratics can be viewed was coded as an instance of *insider Negotiability of the Enterprise* and *inbound Nexus of Multimembership.* She is recognizing how both science and music are needed together to create the rooms that hold the Quavers to Quadratics activities for the children.

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