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Enhancing Student Learning Through Facilitating Informal Programs

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ABSTRACT: There is growing evidence in literature that university students who facilitate informal outreach programs enrich their educational experience through building their scientific identity, sense of belonging to the community, and important career skills. These features are shown to potentially help with students' persistence in STEM majors and retention efforts. In this study, we explored self-reported student experiences and perceptions of their learning due to their facilitation of informal physics outreach programs. We identified important themes related to students' learning in 35 interviews with undergraduate and graduate students who facilitated at least one out of five informal physics outreach programs at a large, public university. These findings were based on multiple learning theories with a deductive coding process. Through a network analysis with a clustering algorithm, we identified three distinct clusters of themes which we termed: disciplinary learning, internal development, and external engagement. These clusters exhibit ideas centered on developing knowledge and skills directly related to physics, transformation of students' perceptions of themselves and their place relative to the discipline, and authentic dialogic communication with the general public and peers. Statistically significant links between the clusters suggest that the rich learning experience of STEM students who facilitate informal outreach programs rests on the interconnectedness of these themes.

INTRODUCTION

The process of student learning involves both disciplinary and non-disciplinary changes that students undergo over years as part of their educational careers. While much of this learning takes place in the formal classroom, significant growth also occurs in informal spaces, such as co-curricular activities. One such type of co-curricular activity is students working to help run, or facilitate, STEM outreach programs. Such programs are often created with a goal of increasing K-12 students' interest in STEM fields, improving their subject knowledge, and providing awareness about career opportunities. They vary in scale and frequency of events, running from large science and engineering festivals to smaller ambassador programs; they can be delivered in person or through social media platforms (National Research Council, 2009; National Research Council, 2015). These programs are called outreach, public engagement, or informal programs emphasizing that these activities are happening outside of a classroom. If run by a university, outreach is usually considered to be service provided by university professors, staff, and students to the general public. However, there is growing evidence that the impact of outreach programs is broader than serving the public only; equally important, these programs enrich the educational experience of university students who facilitate them (Bergerson et al., 2014; Clark et al., 2016; Fracchiolla et al., 2020; Garner et al., 2018; Garrett et al., 2023; Hinko & Finkelstein, 2013; Perry et al., 2021; Randolph et al., 2022; Rethman et al., 2021; Tillinghast et al., 2020).

Prior Studies. Many colleges and universities in the United States run STEM outreach programs to engage with their local communities, and sometimes to meet the expectations of broader impacts from funding agencies. These programs can often be flexible, providing opportunities for student ownership and innovation. Due to the rich opportunities these programs provide, it is essential to better understand the potential impact they can have on the university students who facilitate them.

Prior research has indicated that facilitation of outreach programs helped students develop their STEM identity. That is, helped them build their STEM "voice" and consider themselves as "STEM people" who belong to the STEM community (Bergerson et al., 2014; Fracchiolla et al., 2020; Garner et al., 2018; Randolph et al., 2022; Rethman et al., 2021). These are important findings since prior studies show that the development of disciplinary identity can positively influence students' persistence in the STEM fields and contribute to retention efforts (Hazari et al., 2010), especially for underrepresented groups (Hazari et al., 2013; Hyater-Adams et al., 2019; Papafilippou & Bentley, 2017; Randolph et al., 2022; Steinke, 2017). As noted by Ufnar et al. (2021), graduate students who engage in outreach can gain skills that are often not cultivated in traditional research programs. Working with informal programs has been shown to broaden students' views on potential career choices (Houck et al., 2014; Laursen et al., 2012). Other important student experiences that emerge from the facilitation of outreach programs include student networking with professors and peers, student recognition by the public as STEM professionals, a higher personal value of public speaking skills, improved communication skills, development of design skills, and student ability to connect science and engineering concepts with real-world situations (Bergerson et al., 2014; Caldwell et al., 2007; Clark et al., 2016; Rethman et al., 2021; Tillinghast et al., 2020). Though some barriers may exist to students engaging in outreach programs, such as language, culture, and gender (Santos-Diaz & Towns, 2020) students working with informal programs have often reported positive impacts to their own well-being and interpersonal skills through authentic interactions with younger learners (deKoven & Trumbull, 2002; Rao et al., 2007).

Our prior research focused on the impact of informal physics outreach programs on university student development (Rethman et al., 2021). This mixed-methods study included surveys and interviews with undergraduate and graduate students who facilitated at least one of five physics outreach programs run by a physics and astronomy department at a land-grant university. We found that facilitation of physics outreach programs improved students' motivation and positively impacted their physics identity and sense of belonging to the physics community. Students reported on developing important 21st century career skills such as communication, teamwork, creativity, and design (Heron & McNeil, 2016). By facilitating outreach, students experienced transformational experiences, improved their confidence and conceptual understanding of physics, and were able to see real-world connections. Our subsequent study indicated an important impact of facilitation of physics outreach on female students, who are usually underrepresented in physics (Randolph et al., 2022). We observed a statistically significant shift in their confidence in their choice of the physics major, and themes indicative of positive persistence and a growth mindset.

In the present study, we focused on exploring the impacts on student perceptions of their learning that the facilitation of informal physics programs provided. We took a broad learning sciences view of learning as being both a process of change for students as well as indicators of growth related to disciplinary and non-disciplinary knowledge (Sawyer, 2005). Growth and learning within a discipline are one of the most important outcomes of a students' university experience. Prior literature indicates that when students know they will be expected to explain concepts to other people as well as answer their questions, they are motivated to learn that material more deeply (Kobayashi, 2019). This connection is enhanced through the work of Fiorella & Mayer (2013) who found that "learning is enhanced through the act of teaching others"; that is, students develop a more robust understanding of content when they present a lesson on that material. Students' opportunities to teach are often done through teaching assistant or learning assistant positions in a classroom setting. Student learning and teaching through informal physics outreach programs is less known and studied. However, research on one after-school informal physics program, where trained university students taught middle school youth, reported a positive influence on university students' attitudes towards teaching and learning (Bennett et al., 2020; Hinko & Finkelstein, 2013; Hinko et al., 2016).

It is worth noting that the students involved in informal outreach programs are often engaged in methods of self-explanation of the physics concepts to diverse audiences (Hinko et al., 2016; Rethman et al., 2021). Self-explanation is a method of actively processing new information by restating it in more familiar terms, relating it to existing knowledge, and making inferences (Chiu & Chi, 2014; Kobayashi, 2019). Through communication with the public and through self-explanation, the informal programs potentially provide university students with opportunities to enhance their disciplinary teaching and learning. This is supported by results from Feldon et al. (2011), who noted that graduate students who were assigned teaching duties in their first years of graduate school developed more robust skills in creating testable hypotheses compared to those who did not teach. While student participation in this latter study was part of a formal appointment, it is a common idea that teaching others improves an instructor's understanding of the content they are delivering.

Learning Theories and Research Questions. The broad and vibrant landscape of outreach programs provides students with opportunities for learning experiences beyond those related to a discipline in classroom or laboratory contexts. These learning experiences can be characterized as changes within the students including transitioning from being a novice to becoming an expert, transforming due to authentic experiences, identifying oneself as a member of the physics community, changing assumptions about the responsibilities of physicists, and encouraging physics identity development. To adequately characterize the complexity of these learning experiences, no singular theory or framework seemed suitable. To encapsulate the individual, social, and dynamic nature of interactions that students experienced when facilitating outreach programs, we selected a set of learning theories: social constructivist theory, situated learning theory, transformative learning theory, and constructionist theory.

Each of these theories has been operationalized in studies of similar focus to the one described here. Garner et al. (2018) employed a constructivist approach to analyze the emergence of particular role identities for undergraduate engineering students. Fracchiolla et al. (2020) drew on both constructivist and situated learning theories in applying a community of practice framework to understanding identity development from select interviews with two graduate students in physics who worked regularly with outreach programs. Transformative learning theory, essential in characterizing shifts in beliefs and perspectives, was employed by Rethman et al. (2021) for a similar study drawing on a few dozen interviews with both undergraduate and graduate physics students. Constructionist theory was operationalized by Vaccaro and Newman (2016) when interviewing 51 first year college students to explore their definitions and development of a sense of belonging.

Building on the foundation of work described above, we sought to broaden the understanding of the impacts of students facilitating informal programs by specifically focusing on the process of change or learning that may occur as a result of working with co-curricular programs. Using the database of interviews collected as part of our prior study (Rethman et al., 2021), we sought to answer these research questions: (1) What are students' perceptions of their learning that results from engaging with informal physics outreach programs? and (2) How are these perceptions of learning interrelated with other important constructs such as disciplinary identity and sense of belonging to the STEM community? We hypothesized that students who teach physics to public audiences through informal programs would report enhanced learning of concepts and synthesis of physics knowledge and experience internal development. In the following sections, we present the physics outreach programs included in this study, our methods, including the theoretical framework, results and discussion, and end with some concluding remarks. Although in this study we concentrate on the student experiences within physics outreach, these results can be applicable to other STEM outreach programs.

PROGRAM DESCRIPTION

This study focused on students who engaged with at least one of five informal physics outreach programs, described in Table 1, run by the Department of Physics & Astronomy at Texas A&M University. The goals of these programs are to make physics accessible to the public and, equally important, enrich the educational experiences of university students who facilitate them. In this context facilitation is defined as students taking on roles through which they present and demonstrate physics phenomena to general audiences. The scope of these events range from a signature, large flagship event once per year which includes talks from prominent physics and astronomy speakers and professional science entertainers, to almost weekly events for K-12 student groups and community events. At the heart of all these programs are hands-on demonstrations, many designed and built by teams of students, which connect student facilitators to the audience through their shared experiences with physics.

While each of the programs in Table 1 was founded in different years and focuses on different audiences and scales,

Table 1. *Description of informal physics outreach programs facilitated by undergraduate and graduate students included in this study. The title of the program, the first year of its implementation, the number of student facilitators (N) working with the program per year, and a brief description are included.*

Program	Began	N	Description
Discover, Explore, and Enjoy Physics & Engineering (DEEP) https://artsci.tamu.edu/physics-astronomy/outreach/deep/index.html	2021	70	Two-semester high impact program where graduate students lead teams of undergraduates to research, design, fabricate, and present physics demonstrations.
Physics & Engineering Festival https://physicsfestival.tamu.edu/	2003	300-400	Annual flagship event open to the general public, with thousands of attendees coming to engage with hands-on demonstrations and science lectures.
Physics Show https://physicsshow.tamu.edu/	2007	200	On-campus event for K-12 student groups, including a presentation and interactive hands-on demonstrations.
Real Physics Live https://real.physics.tamu.edu/	2016	11	Short, educational and entertaining videos created by students that explain physics phenomena at the level of middle school students.
Just Add Science & Game Day Physics https://justaddscience.tamu.edu/ https://gameday.physics.tamu.edu/	2015	70	Presenting hands-on demonstrations at community events, to meet people where they are already gathered.

they all provide students with potential opportunities for experiential learning, peer learning and mentoring, networking across departments, and developing essential communication skills as well as for growing teamwork and leadership abilities. A more detailed description of these programs is available in Rethman et al. (2021). We would like to note that one of the authors, TE, is the founder and/or organizer of the outreach programs described in this section. Two other authors, JP and CG, were formerly active participants in multiple programs.

METHODS

To explore student learning that may occur through facilitation of informal physics outreach programs, we examined 35 interviews collected as part of a prior mixed-methods study, described in Rethman et al. (2021). Interviews were conducted by a researcher unfamiliar with the subject, to avoid any potential bias, and included 11 women and 24 men who facilitated at least one informal physics outreach program while being an undergraduate or graduate student at a large, public institution between 2013-2019. These interviewees were recruited from more than 100 respondents to a survey sent out in fall 2019. Each interview was semi-structured and consisted of six didactic questions (see Appendix) that were intended to probe constructs related to physics identity, worldview, and goals developed collaboratively between physics education researchers and learning scientists (Randolph et al., 2022). Interviews lasted between 15-45 minutes and transcriptions of the recordings were created by a professional service. Transcriptions were anonymized before analysis was conducted. Though programs differed in scope and commitment, and our data included responses from both undergraduate and graduate students, we chose to keep all interviews together in a single data set since our prior study found only minor differences between the experiences of the two types of students (Perry et al., 2021). In this section, we describe the framework and code book used to characterize major themes of learning from student interviews. We also describe the methods used to analyze the coded interviews.

Framework. To explore student learning through their experiences facilitating informal physics outreach programs, we sought an approach, aligned with learning sciences (Donaldson & Allen-Handy, 2023), which would allow us to characterize the complex impacts reported by students. While the interview questions (see Appendix) were designed to probe student identity (Rethman et al., 2021), interviewees often touched on topics related to processes of change related to their knowledge as well as self-reported descriptions of changes to their disciplinary and non-disciplinary knowledge, which motivated this study. It is this process of change that we take to be evidence of learning. As discussed in the introduction, the breadth of change evident from the students' interviews led to our selection of four fundamental learning theories for our analysis: social constructivist theory, situated learning theory, transformative learning theory, and constructionist theory. In examining each theory, we considered the core principles for each and, based on our expertise, worked to encapsulate these principles in a finite but descriptive set of deductive codes which we used to characterize student experiences, as expressed in the interviews. Below, we expand on the role of these theories and the codes included from each theory. Other theories were considered but not included as they did not relate to the experiences reported by students.

Social constructivist theory frames learning as being a process of active construction of knowledge, as opposed to passive acquisition, for individuals which can occur individually, collaboratively, and collectively (McLeod, 2025). This theory has also been used to describe the construction of self and meaning, in addition to knowledge, as described in Donaldson and Bucy (2016). Through social constructivism, learners may engage in collaborative construction of knowledge with novices and experts, develop skills in differentiating information and knowledge, and enhance confidence in their own ability to construct knowledge. Codes drawn from this theory related to dialogue between student facilitators and audience, focused on negotiating meaning, scaffolding, and identifying the zone of proximal development (an area which learners may expand into with help and guidance from interactions with someone more knowledgeable).

Situated learning theory describes learning as a process of "becoming" in the context of a specific community, which Wenger suggested relied on social competence and personal experiences (Wenger, 2000). That is, learning occurs through interactions, relationships, engaging in the practices specific to a community or discipline, and a perception of transitioning from being more novice to being more expert through legitimate peripheral participation (Fuller et al., 2005; Lave & Wenger, 1991). Drawing on this theory, we included codes for peripheral participation, physics identity, ways of knowing, and physics practices as they related to self, peers, and the audience. In this work we considered ways of knowing to reflect understanding of physics knowledge or concepts and physics practices to reflect analyzing or questioning in ways that a physicist would. In defining physics identity, we used the physics identity framework as developed by Hazari and colleagues, which draws on the foundations of situated learning theory (Hazari et al., 2010). Within this framework, physics identity relates to student (1) interest in physics or motivation to study physics, (2) beliefs about their performance and competence in physics, (3) confidence and physics self-efficacy, and (4) internal or external recognition as being a physicist.

Transformative learning theory relies on critical reflectivity on the part of a learner (Mezirow, 1981) which facilitates a change in their frame of reference, perspective, worldview, beliefs, or assumptions (Illeris et al., 2009; Kegan, 2018). To be transformative, a learner's viewpoint must be influenced in a way that they may no longer see or think of the world in the ways they did prior to being transformed. Codes related to transformative learning theory included both questioning and changing of assumptions, beliefs, or perspectives connected to physics or the role of physicists.

Constructionist theory is tied to the creation of artifacts, activities, processes, or other observables which are reflective and co-constructive of the ideas and knowledge being constructed (Ackermann, 2001). Through the act of creation students engage in a great deal of productive failure which may also be characterized as an experimental and iterative style of engagement which allows students to adapt their goals along the way (Resnick & Rosenbaum, 2013). Codes related to this theory included making, designing, or building which focuses on the process of creating an asset or process related to physics knowledge, as well as authentic audience, purpose, or impact relating to a change to a student's state of mind or understanding.

In addition to the codes described above, a small number of outcome-oriented codes were incorporated into the code book. These codes were not related to the four learning theories described above, but rather were emergent codes derived from the data. These codes were incorporated to see if there were any systematic connections between the learning experiences described and career trajectory or essential 21st century career skills for physicists as described by Heron and McNeil (2016). These essential career skills, including communication, teamwork, and leadership, are frequently used by recent physics bachelor degree recipients in their careers in both academic and non-academic settings according to data collected by the American Institute of Physics (White, n.d.). If students reported an influence of their experiences in informal physics outreach programs as significantly reinforcing or guiding a decision related to their current degree, future degree, or a career outside academia this was also coded. A total of 23 codes were used in this study.

In applying the lens described in this section to our data, we recognize that the learning described in each theory, and the outcomes are complex and therefore unlikely to be independent or separate from each other (Fischer at al., 2018). Indeed, students' descriptions of their experiences were multifaceted, representing a dynamic and interconnected process of change through their activities with informal physics outreach programs. For this reason, we examined both common themes from the interviews and the correlational connections between ideas using network analysis, described below.

Coding & Analysis. After developing the code book and discussing it with a learning scientist, three researchers split into two teams. Each team coded all of the 35 interviews using the MaxQDA Analytics Pro software, meeting regularly throughout the process to discuss and resolve differences. For this work, we treated complete sentences as our fundamental unit, which is the smallest portion of an interview which contained distinct ideas representing our codes. Only segments which were clearly related to student experiences gained through their facilitation or interaction with informal physics outreach programs were coded. At the end of the coding process, the two teams had an intercoder agreement, which is the fraction of codes in agreement, of $\kappa > 0.9$.

To examine the significant relationships between codes and extract important themes of student learning, we employed a network analysis with clustering. Network analysis may be applied to a variety of systems, including social networks where relationships between individuals may be examined (Notebaert et al., 2018; Wasserman & Faust, 1994) or to systems of ideas, categories, or codes (Christensen & Kenett, 2021; Donaldson & Allen-Handy, 2020;) and provides a valuable tool to investigate complex relationships between different units (e.g. people, ideas, codes) (Segev, 2021). To conduct this analysis, a matrix of Pearson's correlation coefficients are calculated based on the co-occurrences of all pairs of codes across all interviews. For this work, only correlation coefficients with a significance level of $p < 0.01$ were recorded. In MaxQDA Analytics Pro correlations are calculated based on analysis of pairs of codes examining where they do, and do not, appear together in the text of the interviews across the data set. This corresponds to analyzing individual student experiences against each other, as opposed to comparing answers to individual questions during the interviews.

The matrix of correlation coefficients is then used as input to create a 1-mode network using the UCINET network analysis software (Borgatti et al., 2002) to generate a visual representation of statistically significant relationships (edges) between nodes (in this case codes). The sizes of nodes within a map are determined by the eigenvector centrality, accounting for both the number and strength of significant correlations, of a node within the network (Kadushin, 2012; Scott, 2017). In network analysis centrality is based on an individual code's relationship to other codes in terms of distance or steps along edges. Larger nodes represent codes that are more interconnected to other codes both directly and indirectly.

After the network map has been produced it contains nodes and edges representing significant connections. Not all codes may be represented by nodes on the map due to the significance cutoff mentioned above. The next layer of analysis then looks to group these connections into a smaller set of clusters which researchers may analyze for common themes. This is a clustering analysis. On the map shown in the results section, clusters are designated by different colors and shapes of the nodes. Cluster analysis was done using a Girvan-Newman algorithm described in Girvan and Newman (2002). Conceptually, clusters represent a group of nodes which are more strongly linked together than they are to nodes in other clusters. Or more simply, clusters represent a subset of strongly interdependent ideas or experiences. Clusters produced by a Girvan-Newman analysis are considered robust for output values, termed *Q*, that are above 0.30 (Zahiri et al., 2021).

RESULTS AND DISCUSSION

In this section, we present results and discussion from our analysis of interviews with undergraduate and graduate students who volunteered to facilitate one or more informal physics programs. To highlight the major impacts on student facilitators, we focus on the themes most often noted in all interviews, a network analysis of interrelated themes, and relationships between clusters of sets of themes. Included throughout this section are exemplar quotes which are shared to better contextualize the findings of this work.

Frequent Themes Related to Student Learning. The frequency of codes per interview, that is number of interviews which included an idea at least once, is shown in Table 2. A total of eight codes were present in at least two-thirds of the 35 interviews conducted: *scaffolding* (30), *engaging self in physics identity development* (30), *engaging audience in physics identity development* (23), *legitimate peripheral participation* (30), *changing assumptions, beliefs, and perspectives* (30); *authentic audience, purpose, or impact* (33); *non-disciplinary learning* (32), and *disciplinary learning* (24).

Table 2. *Frequency of codes appearing at least once in each of the 35 interviews conducted. Codes are grouped by their learning theory.*

Theory	Code	Frequency
Social Constructivist	Zone of proximal development	3
	Scaffolding	30
	Negotiating meaning with audience	12
Situated Learning	Self - physics ways of knowing	14
	Self - physics practices	7
	Self - physics identity development	30
	Peers - physics ways of knowing	7
	Peers - physics practices	3
	Peers - physics identity development	14
	Audience - physics ways of knowing	5
	Audience - physics practices	3
	Audience - physics identity	23
	Legitimate peripheral participation	30
Transformative Learning	Questioning Assumptions, Beliefs, Perspectives	1
	Changing Assumptions, Beliefs, Perspectives	30
Constructionist	Making, Designing, Building	16
	Authentic Audience, Purpose, Impact	33
Outcomes	Non-Academic Career	15
	Academic Career - Current Degree	2
	Academic Career - Future Degree(s)	8
	Non-disciplinary Learning	32
	Disciplinary Learning	24

In describing the impacts of facilitating informal physics programs on the learning experience of undergraduate and graduate students, it seems only appropriate to begin with *disciplinary learning*. When acting as a facilitator, students had opportunities to deepen their understanding of physics concepts by both building and presenting hands-on, real-world applications to a general audience. From one graduate student's perspective, being a facilitator "definitely helped understand what you're doing...you have to really understand what's going on in order to explain it." For some, this understanding could come in the form of knowledge being more "cemented" or "reinforc[ing] things that didn't make sense while I was in the classroom." For other facilitators, knowledge was extended beyond what was touched on in classrooms, as demonstrations were based on topics beyond the typical curriculum. One student spoke at length of their experience taking over a spintronics demonstration recalling that they "didn't know anything about spintronics until I built this demo." This mirrors results from Caldwell et al., (2007) who saw reports of modest increases in student disciplinary knowledge when they worked with a mentor to develop afterschool STEM lessons for K-12 students.

Students also frequently mentioned *non-disciplinary skills* they improved on through their experiences facilitating outreach, specifically their communication, teamwork, and leadership skills. Students often commented on their growth in "being able to communicate highly technical phenomena to all different levels of people," which was a skill not all students thought they had to master when entering the field of physics. One student exemplified this, stating they imagined a physicist did research in a basement and did "not have to talk to anyone." The team environment of the programs also drove home how essential it is to be able to work with others. One facilitator noted that "you can't do it all yourself...and that you have to lean on others and be part of a team. And it's kind of this type of intangible education that... people can get out of these outreach programs...They're universal skills." Such improvement in communication skills has been noted by multiple prior studies of STEM outreach programs in areas other than physics (Clark et al., 20016; Fitzallen & Brown, 2017; Tillinghast et al., 2020).

Many interviews also covered a transformation for the participant where they changed their assumptions, beliefs, or perspectives. From being placed in the role of a facilitator, participants were put in unique scenarios where they could evaluate and evolve their perspective of physics practices in many ways. For example, a graduate student shared how being a facilitator "made [him] realize an important role...the scientists need to play. [Scientists] need to reach out and tell people about what [they] are doing...be an active proponent of science, of going out into the community, and be engaged with people around us." Other codes listed at the beginning of this section are discussed below as part of the network and cluster analysis in conjunction with themes of learning.

Network Analysis. Results of a network analysis are shown in Fig 1. Here, 17 out of 23 codes, significant at the $p < 0.01$ level, were found to be interrelated. These codes were grouped into three distinct Girvan-Newman clusters (Q=0.423). The remaining codes were not correlated at the level of statistical significance used for this study. After the clusters were identified, the research team discussed common trends and themes amongst the nodes to determine a fitting label for each cluster. Based on our interpretation, we labeled them as: disciplinary development, internal development, and external engagement. We expand on, and discuss, each of these clusters below.

Disciplinary Development. The first cluster, represented by the black triangles in Figure 1, contains themes around *disciplinary development*. Within the network, we observed themes that involved students applying and refining their disciplinary knowledge from their current degree in creating new demonstrations and presentations to share with audiences. Students noted that "to explain physics demonstrations to people who know nothing about physics, you have to explain it really well. And in order to explain it really well, you have to understand it really well." Further, this growth in physics disciplinary knowledge was interrelated with the process of engaging in the making, designing, and building of demonstrations for physics outreach programs. Facilitators could work on projects which touched on physics topics they had "never learned" before where they were "building up a scratch idea from physics" that ended up being "really helpful" for expanding their knowledge. They were also immersed in a community of practice providing opportunities for unexpected and unplanned interactions. For example, one student described the "room which is where we build all these demonstrations and work together on the teams and you'd be working on something and then because of this opportunity sometimes somebody asks you a question about

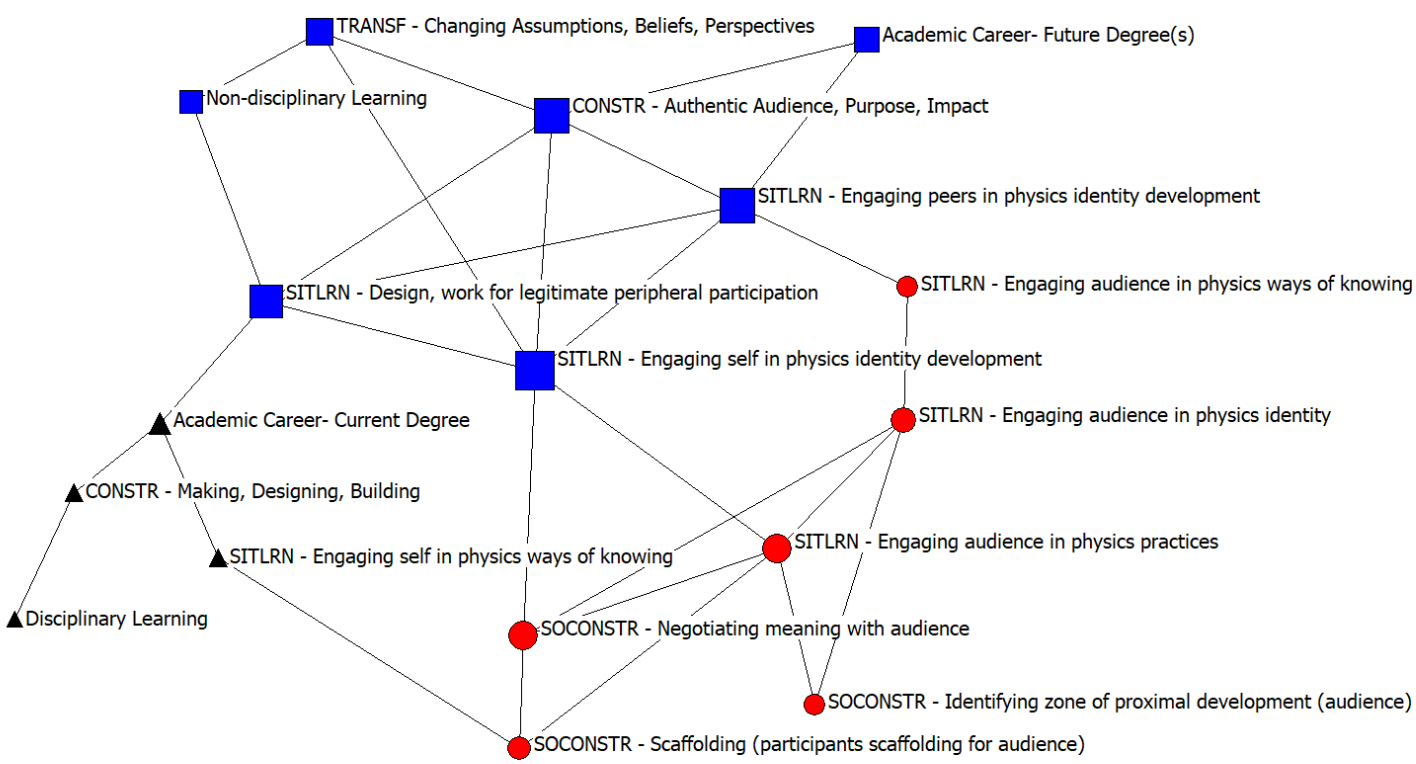

Figure 1. Network map of connections between learning codes significant at the $p < 0.01$ level. The size of the nodes is determined by their eigenvector centrality. Colors and shapes of the nodes denote distinct clusters, Q = 0.423, of statistically interconnected ideas as determined by a Girvan-Newman clustering analysis. Black triangles indicate themes around disciplinary development; blue squares indicate themes centered on students' internal development; red circles indicate factors related to external engagement. Learning theories used in the data analysis: TRANSF = transformative learning theory; CONSTR = constructionist theory; SITLRN = situated learning theory; SOCONSTR = social constructivist theory.

something that's not even related to the project you're working on but something related to some physics thing that they were struggling with... but its given you these opportunities to talk to people and teach and discuss and share ideas and tell stories." This is similar to findings from Ferrara et al., (2018), focusing on undergraduate students working to deliver STEM activities in an afterschool setting to middle and high school students, who reported that students developed a broader understanding of disciplinary content.

Through working within informal physics programs, students reported development of their physics knowledge and ways of knowing. Facilitators attributed informal physics programs as an environment where they developed their disciplinary knowledge beyond the classroom. Students shared that "getting the hands-on experience" of working with demonstrations and "knowing it well enough that you can... teach other people with it was instrumental to me in realizing that I knew physics." These findings mirror prior research which has shown that students benefit from being in a teaching position as they develop and refine an explanation of a topic, leading to deeper learning and increased retention of the content they taught (Coleman et al., 1997).

Internal Development. The second cluster, represented by the blue squares in Figure 1, comprises codes centered on the *internal development* of facilitators. The nodes connected here highlight how students evolved professionally and personally through their facilitation of informal physics programs. Participants shared how they felt "being a [facilitator] and...doing activities involving physics has given [them] a platform...a boost of confidence, a better formal role," and a community of peers. The impact of the programs, from working with public audiences to facilitating with peers or creating demonstrations, helped evolve student perceptions of the field and themselves. From working more with outreach, one student recalled that they "learned that being on your own is kind of untenable when it comes to these bigger [physics] projects," or for another student it "helped me integrate into the physics department and feel more a part of it than before." Here students seem to clearly be indicating their feelings of engagement with a community of practice around outreach, which is an integral part of successful programs that has been noted in some prior research (Ferrara at el., 2018; Fracchiolla et al., 2020).

Central to this cluster was the theme of students moving from being more novice members of the physics community to being more expert members through legitimate peripheral participation. Informal programs provide rich and often unstructured opportunities for students to apply and assess their own abilities and engage in authentic problems related to the discipline, allowing them to grow and realize their expertise. As one student put it, being part of an informal physics program was when they had the sense that others saw them as "someone that should know what they are doing." This was closely tied with a change in physics identity, where students could gain "confidence presenting outreach demos" which could provide a "little surge of confidence every week to go into [their] academics." This aligns with work from Garner, et al. (2018) who observed identity development in engineering students through the social processes of mentoring when cycling through the roles of student, facilitator, and presenter. Their roles within informal physics also allowed students to regularly develop non-disciplinary, or career, skills such as leadership, teamwork, and communication. They also had chances to see new opportunities through working with peers and faculty. Students spoke specifically about interactions which helped them realize there is not one set academic path which works for everyone. Instead "there are other routes, and they're not any better or worse", which helped some students feel more comfortable with their personal plans and trajectory.

External Engagement. The third cluster in Figure 1, shown by the red circles, represents factors related to *external engagement*. These factors revolved around facilitators self-analyzing their skill development from engaging with audiences during informal physics programs. Specifically, facilitators discussed how they felt working with an audience with "multitudes of backgrounds and knowledge [levels]," as well as how they benefited from being "able to teach someone and someone. . . asking [them] questions" in return.

One student's experience exemplified how "physics outreach really forces you to be able to explain an idea in a variety of levels" since "you end up talking to people with multitudes of backgrounds and knowledge." Through this student's experience being a facilitator, they have seen "people who have no understanding" and "some people show up, and then they're like, 'Well, actually-' and you're like, 'Yeah. I know. That's right.'" This encouraged negotiations between the facilitator and a diverse audience to establish the audience's current knowledge and allow the facilitator to scaffold their content and effectively communicate. It should be noted that the questioning process and direct teaching motivated students placed in teaching roles to process the material at a deeper level. Prior research has discussed asking and answering questions as an advantage when it comes to students' learning because it requires them to look at the material from multiple perspectives (Kobayashi, 2019). Starr and Minchella (2016) also observed students developing their skills and disciplinary understanding through tutoring, a different type of informal engagement in which undergraduates may hone their knowledge.

These conversations between student facilitators and the public also encouraged audiences to participate in the demonstrations and develop science-like practices and ways of thinking. Facilitators identified these interactions as developing audience members' physics identities while they progressed towards their zone of proximal development and reached a deeper understanding of what was being presented. One student commented on a time where "a little girl... came up to [her] after explaining one of the big explosion demos and she was just like, 'You are so cool. How do you explain that? Where did you learn all this stuff?'" The way that this facilitator interacted with the audience encouraged interactions, as shown by the audience member asking multiple questions. These interactions have been further analyzed from the audience's perspective in other studies with similar contexts. A recent study from Finn et al. (2023) found a positive association between K-12 students actively asking questions and doing experiments with their identity as a scientist.

Lastly, facilitators noted that developing their physics identity also impacted the audience's ways of knowing. As exemplified by one facilitator, they have seen the audience "want to see how lasers work. . . they want to see hover crafts and all that." And when the student shared their explanations, the audience "intuitively get the concepts behind it." Thus, the facilitators asserted their belief that when the audience appeared more motivated and engaged with the physics behind the demonstrations, they appeared to process the information that facilitators shared more effectively.

Connections Between Themes. While each cluster represents an important theme of learning, there are also connections between each cluster which represent important links between the themes discussed above. The clusters of *disciplinary development* and *internal development* are connected along the edge between legitimate peripheral participation and students' current degree. Through their experiences facilitating informal programs, students both developed their disciplinary knowledge in physics and experienced a strong sense of moving from more novice to more expert. This was observed in interviews as higher certainty in, and more refined plans for, completing degrees, often as in engaging in research efforts. This connection may also be observed for students who have not engaged in informal physics programs, as progression through a degree may encourage more expert-like identity as well. However, the centrality and size of the nodes in Figure 1 demonstrate that these were major themes in the interviews analyzed for this study.

The clusters of *disciplinary development* and *external engagement* formed connections from facilitators reflecting on their ways of knowing while scaffolding information for the audience members. By interacting with "people who are not 'physics people'," facilitators inherently were able to check their own understanding along the way as they built upon the audience's understanding by scaffolding the needed information. Informal physics programs provided ample opportunities for students to scaffold their knowledge for audience members ranging from 5 to 95 years old and from those new to physics to those with significant knowledge. Through these dynamic interactions, students reported improvements to their comprehension of topics covered in classes beyond the level of simply being able to pass exams. Being a facilitator "helps [the students] interact with people who might be able to correct things that [the facilitator] didn't understand," making the interaction mutually beneficial. This connection is of particular importance to note as interactions with the general public provide significant opportunities for facilitators to think on their feet, to be creative with their explanations and analogies, and to have to respond to unexpected questions from their audience.

Internal development and *external engagement* connect along three different edges, with students' own physics identity development connecting to both negotiating meaning (of physics concepts and ideas) and engaging audiences in physics practices, as well as recognizing their peers' physics identity development with observing audiences engaging in physics ways of knowing. Students reported that delivering their explanations was "a really good form of practice" and they got "exposure to the way people think" through discussing the physics concepts behind the demonstrations with audience members. A similar impact was also observed in a study of the Chicago EYES program where the program facilitators reflected on their experiences compared to the audience's. Facilitators connected their discomfort in presenting with the discomfort the audience shows while they are learning new content (Mekinda et al., 2022). Additionally, these negotiations of physics concepts and ideas "translated to the classroom" and contributed to the students' development as physicists, engaging them in their physics identity development. When observing their peers presenting demonstrations facilitators simultaneously noted the audience developing their ways of knowing in receiving the information, and their peers growing in their physics identity from discussing physics. The students' peers had the opportunity to demonstrate fundamental components of physics and "connect [them] to the broader research...like in [their] own labs" for the audience. This dialog with a diverse audience, which at times led to achieving a common understanding, was seen by researchers to be related to growth in students' physics identity. These themes are well-aligned with discussion from our previous study, where facilitators reported a transformation in their beliefs about the role of science in society (Rethman et al., 2021).

Limitations. The findings noted above show a tangible connection between students facilitating informal physics programs and their learning. However, we must note some important limitations to these findings. All interviews comprised self-reported data from students at a single large, public university with a well-developed outreach program.

Also, all participants in this study were self-selected volunteers from a pool of students who had participated in at least one informal physics program. Future work which includes responses from students who do and do not participate in informal programs, and represent diverse institutional environments would allow for more robust findings.

Conclusions. This research is significant in its focus on the learning experienced by university students working to facilitate informal physics outreach programs as opposed to focusing on audiences of K-12 students or members of the general public. A substantial amount of learning takes place outside the classroom, particularly at the undergraduate and graduate levels. While this learning is often focused on course work it can also take place through co-curricular activities, such as informal outreach programs. Our study generated new knowledge on the learning which occurs when university students facilitate informal physics outreach programs, sharing science with public audiences. Through examination of 35 interviews with undergraduate and graduate students from a large, public, research-intensive university, our analysis showed significant themes of learning for both disciplinary knowledge and non-disciplinary skills. This was evident through students describing their awareness of synthesizing knowledge they were originally exposed to in courses, developing an increased array of real-world connections of their physics knowledge, and refining various skills (e.g. circuit building).

A synthesis of the relationships between learning themes were encapsulated by three clusters of strongly interrelated ideas which we described with the labels of *disciplinary development*, *internal development*, and *external engagement*. Although the interview questions did not ask about learning, students often spoke about experiences—both specific and general—where creating demonstrations, working with peers to facilitate programs, or engaging with a general audience promoted a greater breadth and depth of knowledge. Through feedback from audiences, their peers, and self-reflection, facilitators also built an awareness of their transition from more novice to more expert scientists. Statistically significant links between these three clusters indicate that the student learning and growth gained through facilitation of informal outreach programs are intertwined. In other words, these themes of disciplinary development, internal development, and external engagement are interdependent features of the experiences that may not be separable.

As STEM departments across the country run a variety of outreach programs, it is important to understand the impacts of these informal outreach programs not just for the public, but also for the students the colleges and universities educate. Currently, the role of informal outreach programs in academic programs is underestimated. Our findings indicate an impact on learning as a consequence of student participation in informal outreach programs. We hope that these findings may be used to encourage a more regular component of outreach for STEM students in departments across the country. Further, these findings may be used to encourage a shift in how faculty contributions to colleges and universities are assessed. Outreach could move from the service pillar to the teaching pillar as there is clear evidence that these programs support the teaching mission of a department.

Future research in this area should expand on this initial study to examine impacts of outreach on a national audience, drawn from colleges and universities around the country. To provide more robust results, we plan to collect data with samples including both students who do and do not regularly participate in outreach to better assess the overall impact of facilitating informal STEM outreach programs.

ASSOCIATED CONTENT

Supplemental material mentioned in this manuscript can be found uploaded to the same webpage as this manuscript.

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