Broadening Student Learning through Informal Physics Programs

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Student learning at the university level occurs in a variety of settings, both formal and informal. Prior research shows that retention of knowledge is enhanced when students teach material related to their learning. In this study, we explored student perceptions of learning experienced through facilitation of informal physics programs, also called outreach, where they frequently practice methods of self-explanation to diverse audiences. To characterize the impacts of these facilitation experiences, we employed a student-centered investigation drawing on self-reported data gathered through didactic interviews conducted with 35 students who facilitated at least one of five informal physics programs. Analysis of interviews drew on multiple learning theories to characterize perceptions of understanding of physics concepts, confidence in their knowledge, and how those constructs related to engagement with members of the public through outreach. Using network analysis, we found three distinct clusters of themes focusing on disciplinary learning, internal development, and external engagement.

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I. INTRODUCTION

Informal physics programs, also called physics outreach or public engagement programs, have the potential to enhance the educational experiences of university students. Recent research shows that students who were involved in facilitation of informal physics programs reported a positive development of their disciplinary identity and sense of belonging to the physics community [1, 2]. These are important factors that could help retention efforts in physics, especially for underrepresented groups [3–5]. Other important student experiences with informal physics programs include teamwork opportunities and improvement of student communication, presentation, and design skills [2, 6]. This development of important career skills may be achieved through student explanation of the physics concepts to the general public or team members and fabrication of new physics demonstrations [2, 7].

Students who facilitate informal physics programs are frequently engaged in methods of self-explanation to diverse audiences [2, 8]. 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 [9, 10]. Prior literature indicates that students learning of new concepts deepens when they are expected to explain the concepts to other people [10]. Moreover, Fiorella et al. states that "learning is enhanced through the act of teaching others"; that is students tend to develop a deeper and more persistent understanding of material when they present a lesson, rather than just preparing to give a lesson [11].

Students who have the opportunity to teach have traditionally done so through positions such as being a teaching assistant or learning assistant. Informal physics programs provide university students with rich opportunities for teaching and learning in environments that are less structured, lower stakes, and often more exciting than regular classes. By design, these programs have more flexibility for student ownership, creativity, and innovation and have to be studied more thoroughly since many universities and colleges in the United States are running informal physics outreach programs. A study of one after school physics program facilitated by University of Colorado, Boulder students provided the community with findings demonstrating a positive influence of this experience on university student perspectives on teaching and learning [7]. Subsequent studies of the same program identified and refined an instructor pedagogy in informal physics learning environments [8, 12].

This study focused on exploring the impacts on student perceptions of their learning that facilitation of informal physics programs provides. We predicted that students who teach physics to public audiences through informal programs would report enhanced learning of concepts and synthesis of physics knowledge. In the following sections, we present our methods, including the theoretical framework, results and discussion, and end with some concluding remarks.

II. METHODS

To explore the learning that may occur through the facilitation of informal physics programs, we analyzed a series of 35 interviews, 11 women and 24 men, collected as part of a prior mixed-methods study [2]. Interviews were conducted with undergraduate and graduate students who facilitated at least one informal physics outreach program between 2013-2019 at Texas A&M University, a large, land-grant institution. Facilitators were engaged with at least one of five informal physics programs ranging from large annual festivals to smaller engagements with the general public happening throughout the year. Each interview was semi-structured, conducted by a researcher unfamiliar with the interviewee, and consisted of a set of six didactic questions developed in collaboration with learning scientists. These questions probed interviewees on how they saw their experiences with facilitating informal physics programs relating to constructs such as physics identity, worldview, and goals [5].

For this study, we related physics learning to growth in disciplinary knowledge as well as a broader process of change within students. These changes were expressed in multiple ways, including: transitioning from novice to expert perspectives, identifying as a member of the physics community, changing assumptions about the responsibilities of physicists, transforming due to authentic experiences, and encouraging physics identity development. To account for the complexity of learning experiences, we developed a code book based on four fundamental learning theories. The theories we drew on included social constructivist theory, situated learning theory, transformative learning theory, and constructionist theory.

Social constructivist theory asserts that knowledge is constructed through an active, social process where learners make connections between their background and new information [13, 14]. Codes drawn from this theory related to dialogue between facilitators and audience, focused on negotiating meaning, scaffolding, and identifying the zone of proximal development. Situated learning theory connects learning to interactions, relationships, engaging in the practices of a community, and an overall sense of transitioning from a novice to an expert through legitimate peripheral participation as newcomers grow in to experts [15, 16]. Related to this theory, codes for peripheral participation, as well as physics identity, ways of knowing, and disciplinary practices as they related to self, peers, and the audience were included. In defining physics identity, we drew on the physics identity framework developed by Hazari and colleagues, which includes interest/motivation, performance and competency beliefs, and internal/external recognition [3]. Transformative learning theory is concerned with changes in a learner's "frame of reference", or perspective, worldview, or assumptions [17, 18]. Codes related to the questioning and changing of assumptions, beliefs, or perspectives connected to physics were included from this framework. Constructionist theory frames learning as being tied to the creation of artifacts, activities, processes, or other observable things which

were reflective of the material related to what is being constructed [19, 20]. Codes related to this theory included making, designing, or building, as well as authentic audience, purpose, or impact which relates to activities and processes. Other learning theories were considered but omitted from this study as they did not describe the types of learning observed through informal physics programs. We also included important outcomes related to learning, such as career skills and future plans. A total of 23 codes were used in this study.

After developing the code book, three researchers split in to two teams and coded each interview while meeting regularly throughout the process to discuss and resolve differences. For this work we treated complete sentences as our fundamental unit, the smallest portion of interviews which could contain distinct ideas representing our codes. After completing this process, the two teams had an intercoder agreement of $\kappa > 0.9$. We examined the relationships between codes through network analysis. Network analysis provides a visual representation of statistically significant relationships between nodes (in this case codes), as well as highly interrelated clusters of nodes. By calculating correlation matrices and determining the centrality of each idea through eigenvector measures, a map is produced where edges (lines) show statistically significant connections at an assigned level, $p < 0.01$ for this study. Larger nodes and a higher number of edges are related to the eigenvector centrality of a node within the framework [21, 22]. Clusters within the map are designated by different colors and shapes of nodes, where clustering was done with a Girvan-Newman cluster analysis [23]. The clusters produced by this analysis are considered robust and an accurate representation of relationships when a value, termed Q, is above 0.30. Each cluster represents a group of interrelated nodes which are more strongly linked together than they are linked to nodes in other clusters. In other words, clusters represent a subset of interdependent ideas.

III. RESULTS & DISCUSSION

In this section, we present initial results from our analysis of interviews with undergraduate and graduate students who facilitated one or more informal physics programs, and discuss their implications. Results of a network analysis, at the $p < 0.01$ level, shown in Fig. 1, include 17 out of 23 codes which are grouped into three distinct Girvan-Newman clusters ($Q = 0.423$). The remaining codes were not correlated with others at the level of statistical significance used for this study. Three clusters were identified. Based on our interpretation we labeled them as: *disciplinary development*, *internal development*, and *external engagement*. Each of these clusters is discussed below.

The first cluster we will discuss is represented by the black triangles in Fig. 1. Within this cluster we observe themes around *disciplinary development*. 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 over a topic, leading to deeper learning and increased retention of the content they taught [24].

Within our network, these developments were related to students' current degree plans and opportunities to create new demonstrations and share them with audiences. When working in a program to design or build new demonstrations, students were placed on a team with other members of varying levels of knowledge, from undergraduate freshmen to graduate students. One student shared that his team developed a bond as they would discuss "anything from... how they became physicists, to what their study is," exposing each other to their individual fields of interest. That student also shared that they were offered a "research opportunity [that] would not have come about if [they were] not a part of the [program] and doing outreach". Through informal physics programs, students formed meaningful connections with others in their discipline. From having unstructured interactions with others, students were also able to expand their physics knowledge, and refine their current degree plans.

The second cluster we will discuss is represented by the blue squares in Fig. 1. These codes are more focused on the *internal development* of facilitators. These interdepencies highlight how students have evolved through their facilitation of informal physics programs individually and through peer interactions. In multiple interviews, students reported that they have developed their sense of responsibility through their engagement with informal physics programs. As one student shared, working with a team as part of an informal physics program was when they had a sense others looked at them "as someone that should know what they were doing." Additionally, facilitators reported their beliefs regarding academic responsibilities evolved to include a more comprehensive view of their opportunities. One student mentioned that getting to interact with peers and faculty during informal physics programs led to them fully realizing that there is not one set academic path which works for everyone pursuing a physics degree. Instead, "there are other routes, and they're not any better or worse" than one another. Another student commented that after hearing their peers discuss their ideas and goals, they felt better exposed to opportunities available to them, stating that they "didn't know that [those goals] were things you could do". These experiences were reported to have influenced the participant's perspective of themselves as they progressed from being seen as a novice practitioner to holding a position of greater expertise. This was related to participants' learning of nondisciplinary qualities such as leadership and communication skills. Students also reported on refined ideas of what they would pursue after complet-

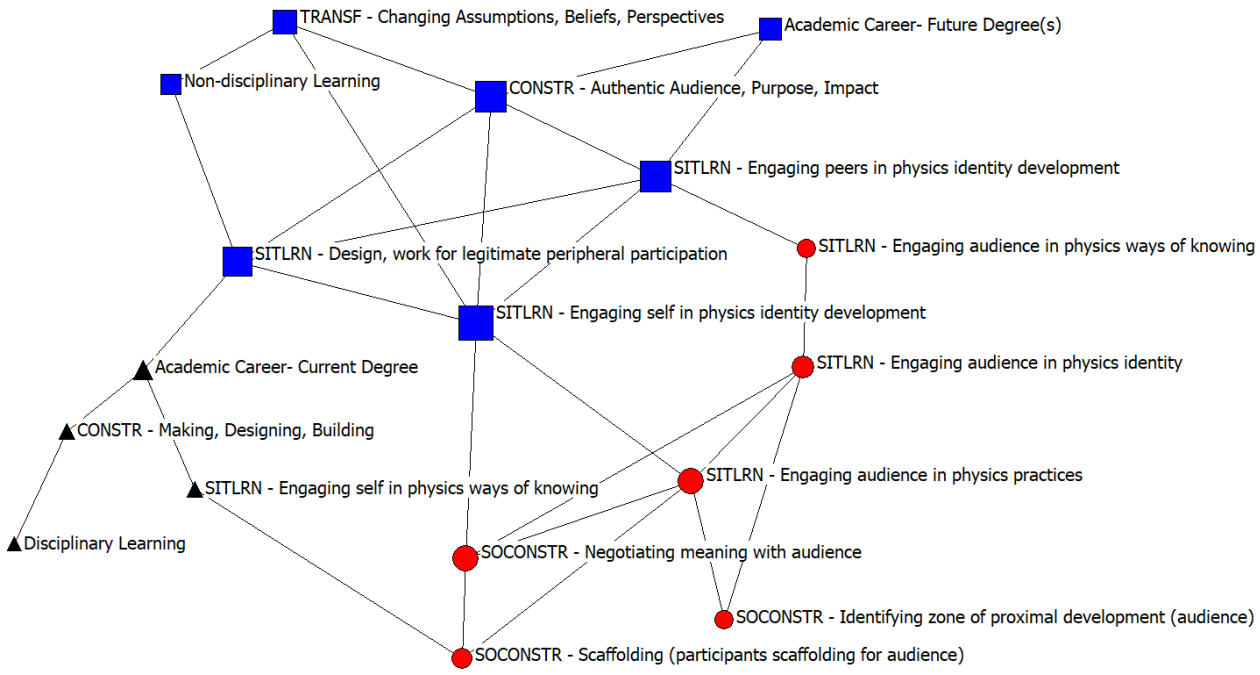

FIG. 1. Network map of relationships between learning and outcome codes at the $p < 0.01$ level. The size of the nodes indicate their Eigenvector centrality. Colors and shapes of the nodes denote distinct clusters, $Q = 0.423$, of statistically interconnected ideas representing more closely related themes as determined by a Girvan-Newman clustering analysis.

ing their current degrees. One student in particular shared how they knew they wanted to continue working with children because of "this moment of clarity" where they better understood "who [they] wanted to be" professionally. In relation to physics identity, facilitators reported direct impacts from their experiences in outreach to improvements in their interest and motivation to learn more physics, as well as their confidence and competency beliefs in what they had already learned. From one student's experience, they noted that these changes were "mostly due to me having that confidence presenting outreach demos and just having that little surge of confidence every week to go into my academics and presentations." Overall, interviewees shared that informal physics program opportunities provided an environment for them to engage with others in and outside of their discipline, which created the necessary authentic setting needed to transform their perceptions of their physics identity.

The third cluster in Fig. 1, indicated by the red circles, represents factors related to *external engagement*. These factors revolved around facilitators discussing their development of skills in engaging with audiences during informal physics programs, as well as evaluating the effectiveness of their explanations. One student shared 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 motivates 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 [10]. 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. 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 expla-

nation, 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.

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. Based on our analysis, connections between *disciplinary development* and *internal development* formed as students progressed in their current degrees and their peripheral participation. Informal physics experiences allowed students to feel more a part of the field, growing from novices to experts, and for some resulted in higher certainty and more refined plans for completing their degrees, such as engaging in research efforts as mentioned previously.

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'" inherently, facilitators 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 understanding 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.

Internal development and *external engagement* connect along three different edges. The first occurred with facilitators recognizing their peers physics identity development while also evaluating the audience's ways of knowing. Students reported that when observing their peers presenting demonstrations they 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 student's peers got 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. *Internal development* also crossed into *external engagement* when facilitators reported on their own physics identity development while either negotiating meaning with the audience or encouraging the audience to engage in physics practices via hands-on demonstrations. 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. Additionally, these negotiations "translated to the classroom" and contributed to the students' development as physicists, engaging them in their physics identity development. Leading the audience through understanding a demonstration helped students feel most like a physicist and enhanced their feeling of expertise.

IV. CONCLUSIONS

This study expands on prior analyses of student experiences gained through facilitation of informal physics programs to analyze perceptions of student learning, an important dimension of their experience as undergraduate or graduate students in physics. Our examination exhibited three distinct clusters or types of learning: *disciplinary development*, *internal development*, and *external engagement*. By engaging with programs that brought students into contact with diverse audiences in less structured settings, they were able to broaden and deepen their understanding of physics content both through the act of creating new demonstrations, and engaging in dialogue with those more novice than themselves to explain physics concepts. Through feedback from audiences, their peers, and self-reflection, facilitators also built an awareness of their transition from more novice to more expert physicists. Statistically significant links between these three clusters indicate that the types of learning and growth reported in the previous section are intertwined. In other words, they are all features of experiences gained through informal physics programs and may not be separable.

While these findings are interesting and contribute to the growing body of literature about the benefits of university students facilitating informal physics programs, we must note some limitations in this study. All self-reported data were collected from a single institution. Students who agreed to be interviewed were self-selected volunteers. Future work in this area will build on these findings and draw from data which includes a larger body of responses from students who did and did not engage in facilitation of informal physics programs.

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