Fostering Belonging through an Undergraduate Summer Internship: A Community of Practice Model for Engineering Research Education

Ms. Nicole Bowers, Arizona State University
Dr. Michelle Jordan , Arizona State University

Michelle Jordan is as associate professor in the Mary Lou Fulton Teachers College at Arizona State University. She also serves as the Education Director for the QESST Engineering Research Center. Michelle's program of research focuses on social interactions in collaborative learning contexts. She is particularly interested in how students navigate communication challenges as they negotiate complex engineering design projects. Her scholarship is grounded in notions of learning as a social process, influenced by complexity theories, sociocultural theories, sociolinguistics, and the learning sciences.

Ms. Kate Fisher
Prof. Zachary Holman, Arizona State University
Mathew D. Evans, Arizona State University

Mathew D Evans is currently a doctoral candidate at the Mary Lou Fulton Teachers College at Arizona State University

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In the 21st century, it is not sufficient for engineering students to acquire good technical skills. Although these are necessary for career success and productive work, students must also develop capacities for authentic engineering practices within authentic engineering communities. Specifically, they must develop practices for engaging ill-structured, ambiguous problems, and navigating complexity and uncertainty through careful, creative application of deep knowledge that characterize engineering design[1]. And they must do so in collaboration with others, communicating successfully with diverse stakeholders in formal and informal settings[2]. Finally, they must cultivate the ability to reflect on the quality of their innovation and communication efforts[3].

The NSF and other sponsors fund research experiences for undergraduates (REU) programs in an effort to more holistically develop future scientists and engineers as described above, but the very asset of the apprenticeship, the highly-situated nature of the REU, presents challenges for program design. REU's typically mirror the laboratory experience of advanced level graduates, with undergraduates working closely with graduate student mentors and situating knowledge in authentic and novel research projects over a six-to-10-week summer program, as opposed to highly structured classroom-style learning models. Historically, many REU's heap the responsibility of leading inexperienced undergraduates in learning and integrating into a new field onto postdoctoral or graduate student mentors who often have "little preparation, support or even rewards for their contribution"[4]. Additionally, NSF encourages REU programs to include freshmen and sophomore students, adding pressure to programs to prepare lower-level students through an apprenticeship model traditionally used for advanced-level graduate students.

Although typical graduate students working in apprenticeship programs are surrounded by social relationships and activities through which the core practices of the engineering community are made visible over long periods of time, the same may not be true for typical REU students working under shortened timeframes and in more peripheral conditions. Typical REU students are legitimately involved in specific laboratory practices but their participation in the field at large remains narrow and implicit due to lack of support in development of research design skills, and professional identity and socialization[4, 1]. Wenger[5] reminds us that "meaningful learning in social contexts requires both participation and reification to be in interplay" (p. 1), but REU participants likely lack opportunities afforded to graduate students to more legitimately participate in the community, given their relative inexperience and contracted timeframe.

While the challenges of attracting, retaining, and educating engineers are well-recognized[6], engineering researchers are divided in their beliefs about effective ways to socialize REU students into the engineering field. Sadler, Burgin, McKinney and Ponjuan[7] call for more explication of concepts, others call for more standardization in assessment and content delivery across research experiences[4] while still others call for complete open-endedness, embracing the apprenticeship as purely experiential learning[8]. We contend that what is needed is a necessary tension between the affordances of contextualized experience offered by typical apprenticeship programs, and the affordances of more highly structured experiences traditionally enacted in classroom environments. Although the situated nature of REU programs presents an important opportunity for undergraduates to learn science through participation in cutting edge research, more support may be needed to accommodate diverse levels of students in REU programs. A comprehensive model of practices associated with the engineering research process, when used by program designers to guide program development and by participants as a cohering artifact, could provide an opportunity for increased belonging through opportunities to engage in and align with engineering practices, and increase self-efficacy related to one's own competence now and in the future.

Currently, few studies provide insight into how structural elements of research experiences for undergraduates (REU) programs support positive outcomes for participants[9]. In this research paper, we present a case study of the design and implementation of an experiential internship program with structural community elements intended to address undergraduates' needs for inclusion and development through careful design of a summer engineering research internship aimed at increasing disciplinary self-efficacy, engagement, and alignment with an expansive range of engineering research practices. Drawing on prior literature on engineering practices and Wenger's[10] community of practice (CoP) framework, we designed two overarching strategies for supporting REU participants' participation in and belonging to engineering. First, we make the practices visible through a model of engineering practices (i.e., the engineering research model, or ERM, discussed below) and, second, we embed community building elements across the program. Using a mixed-method design, we interrogate the ERM model's value for guiding future programs, and present evidence that an apprenticeship program based on a CoP framework, coupled with an explicit representation of the practices common to the engineering community, supported self-efficacy, engagement, and alignment among members of a diverse undergraduate cohort.

Theoretical Framework

In the following section, we first review the original grounding theory of CoP's and explain Wenger's further elaboration on designing for CoP's to include the role of belonging and its constitutive modes as well as community elements theorized to support belonging in a CoP. We then review scholarly literature on the practices common to the broad community of engineering and explain how those practices are represented in the ERM developed by our team.

Communities of Practice

Through a series of ethnographic studies of learning outside of the classroom in formal and inform apprenticeships, Lave and Wenger[11] developed the theory of communities of practice (CoP). Communities of practice cohere socially through a common language, tasks, and ideas of competence among their members. Groups of people make up CoP's, and their collective endeavors as a group define and often codify the COP's sense of competence and belonging. In other words, the theory of CoPs sees learning as a "dimension of social practice"[11] (p.47). This theory represents direct resistance to the idea that knowledge can be transmitted from knowledgeable others (teachers) and acquired by less knowledgeable others (learners); it moves learning into a more situated and collaborative sphere of social action than do other learning theories. In this light, CoP emerges as a particularly appropriate theoretical framework for the clearly apprenticeship approach of programs such as REU's.

Lave and Wenger[11] see learning as legitimate peripheral participation (LPP) through apprenticeship in a CoP, acknowledging that CoP newcomers become part of a community through active participation in practices that represent important skills and knowledge for the CoP. Through continued participation, newcomers master knowledge and skills exhibited by core members in the CoP. Further, Wenger[10] claims that belonging is a hallmark of newcomer learning. Belonging connects to the standards of competence in the social learning systems of CoPs. For example, exhibiting skill in playing the guitar may foster belonging in a rock band.

Wenger[10] theorized that not only do CoP's naturally exist but that they can also be purposefully designed to integrate newcomers. From Wenger's perspective, designing for newcomers is focused on belonging and community elements that support belonging. Wenger identified three modes of belonging that work in concert to varying degrees depending on the type of CoP: engagement, alignment and imagination. We see these three modes as highly correspondent with scholarship in engineering education that connects intentional designing of engineering education experiences to support confidence and self- efficacy, capacity building, and interest development with successful engineering trajectories - particularly for students from populations underrepresented in engineering.[12]

Engagement involves participants physically doing things together, for instance, talking, producing an artifact, or attending events as a group. Engagement in a CoP helps participants understand what expectations are and how the CoP responds to their participation[10]. *Alignment* concerns how participation of newcomers align with standard skills and knowledge within the CoP. Alignment in disciplines like physics or biology would include standard participation in canonical skills like using laboratory instruments or explaining canonical concepts like cellular respiration[11]. We see alignment as resonant with capacity building that has been shown to foster continued successful retention and participation in engineering[12]. *Imagination* concerns newcomers' images of themselves with relation to the CoP. Imagining that you will, in the future, become a research scientist, imagine metacognitive self-evaluation of current skills like writing a research paper; both are forms of imagining[11]. We submit that imagination encompasses the construct of self-efficacy, which has often been associated with positive outcomes for engineering learners[13, 14]. Self-efficacy is a person's judgment of their own capability to "organize and execute courses of action required to attain designated types of performances"[15] (p. 391). This view of self-efficacy coincides with Wenger's construct of imagination in that it is self-regulatory, subjectively constructed, self-fulfilling, and subject to influence by important others[15].

Wenger[11] claims that the three modes of belonging can be found in differing degrees in various CoP's, and that the combination of the modes can help researchers and designers design activities to promote and balance the modes of belonging for newcomers. For example, belonging to the CoP of photovoltaic (PV) engineers may involve a great deal of alignment to well established concepts and skills while belonging to a volunteer group may require more in the mode of engagement. Although the modes of belonging can be thought of as distinct, they work in combination to create an overall experience of belonging for newcomers. Understanding the way that modes of belonging are emphasized and mixed in a CoP can help members design to foster the modes individually and in combination. In fact, strengthening one mode of belonging may give access to another[11]. For example, increasing the mode of engagement in activities like study groups may support another mode of belonging, like alignment.

In Wenger's[11] view, specific community practices remain core activities, but communities should also pay attention to structural community building elements that enhance members' participation including, events, leadership, connectivity, membership, learning projects and artifacts. *Events* can take the form of a shared lunch, field trip or meeting. *Leadership* refers to both formally recognized leaders in a group like a primary investigator (PI) as well as informal leaders that arise like the team member that organizes social outings. *Connectivity* goes beyond organizing events; it includes members brokering relationships between people in the community that may have similar needs or interests. Connectivity is also supported by facilitating communication through multimedia, like having a Facebook page. *Membership* can be considered a reflection on the coherence of the various members in a community and their activities. Members and their participation should not be too diffuse, or a CoP can dissolve. *Learning projects* revolve around pushing the community's practices further. Learning projects should find and fill gaps in practices like working on a new method in biochemistry. Finally, *Artifacts* can illuminate the shared history of a community to help with the tracking of learning projects and membership as well as focus attention on important community practices. For example, many disciplines have a top tier journal as an ongoing artifact that helps to orient their community members around important shared ideas.

With this framework in mind, we designed a social learning system for our REU program around the practices of engineering and Wenger's[11] community building elements. We expected this social learning system to be a more accessible CoP to REU students within the larger community of practice of photovoltaic (PV) engineers; we can think of this as a smaller CoP within a larger CoP. The REU practices were defined by the larger community, but we implemented them in such a way that they are not so spread out in time and space so that newcomers could find a catalyst for growth among the many learning practices, participation opportunities, and social supports.

Designing an Engineering Community of Practices

Drawing on prior literature on engineering practices and Wenger's[11] CoP framework, we designed two overarching strategies for supporting REU participants' legitimate participation and belonging: Making the practices of engineering research visible through a model of engineering practices and embedding community building elements. We discuss each in turn in the sections below.

Making Engineering Research Visible through the Engineering Research Model

In prior experience working with REU participants, several of our team members have noticed that these undergraduates, many of whom are engaging in engineering research for the first time, often struggle to recognize the practices of engineering, understand the relationship among those practices, and realize them in their assigned research projects during the short timeframe of a summer program. Joining our combined experience with our understanding of the importance of reifying community practices to support newcomers' entry into CoP's[5], we created a graphic model of the engineering research process organized around key practices through which these processes are enacted by members of the engineering community (Figure 1).

The Engineering Research Model (ERM) was designed by four members of our research team, two educational researchers (Authors 1 and 2) and two engineers (Authors 3 and 4). The model was derived over multiple iterations of reviewing the literature and discussions among the research team. Additionally, the educational researchers attended lab meetings, observed lab activities, and consulted with the engineers as part of the design process. Thus, we grounded the model in our diverse knowledge of the practices of the actual engineering CoP in which the REU was embedded.

The ERM was created as a template for all of the practices that the REU should include and support. Design of activities and events throughout the REU were based on this model. Thus, the primary purpose of the ERM was to aid newcomers' entry into the practices of engineering by making them visible, examinable, and discussable. However, the model was also useful for us, as program designers, in that it guided our design of instructional supports and participation opportunities for each of the practices. Engineering design is a complex task requiring high levels of general engineering and specific PV knowledge and practices, and also the ability to reflect on the quality of one's own participation in the practices. Our model, seen in Figure 1, reflects this complexity, showing engineering to be composed of two sub-processes (i.e., innovation and communication) linked through metacognitive reflection.

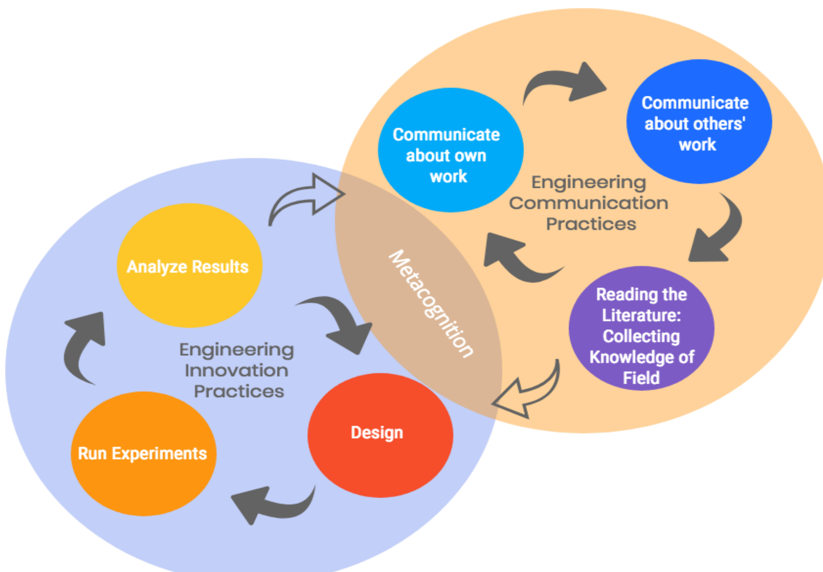

Figure 1. The engineering research model (ERM) as enacted through key community practices

Engineering innovation practices. Scholars have created many models of the engineering design/innovation process, many of which include practices from initial understanding of project specifications all the way through product delivery. As our purpose was a model that could be interpretable and digestible to undergraduate engineering researchers, we distinguish between only three practices central to engineering innovation: designing, running tests, and analyzing results (the latter two are sometimes combined in lab or technical courses[16]).

In our model, the practice of designing entails problem scoping, problem framing, and solution generating[17, 18]. It requires defining problems or research questions that are not only interesting but also important, and assessing the impact of possible solutions or answers. *Designing* and its sub-practices is a crucial capacity often missing from students' engineering toolboxes. It includes formulating, defining, expanding, scoping, representing, finding, and even posing an engineering problem of interest, as well as brainstorming possible solutions to address the problem and a methodology for testing solutions[19, 20]. Executing this methodology relies on practices associated with running experiments, gathering information or data (either in the lab or using simulations), and analyzing results of experiments, which often requires knowledge of sophisticated tools and programs. Thus, designing, running experiments, and analyzing results are iterative and interdependent practices that together comprise the engineering innovation process.

Engineering communication practices. Although engineering communication has a much less robust line of scholarship than engineering design, it is nonetheless recognized as an integral engineering process as engineering is a communication-rich endeavor. Dannels[22] points out that novices need support in the development of communication practices because disciplinary discourse is rooted in traditions that are situated and developed in particular contexts. Engineering communication practices include the ability to use formal and informal avenues to communicate with multiple stakeholder audiences for diverse purposes, whether using verbal, written, or para-linguistic means. It thereby includes not only talking, but also reading and writing in multiple mediums and interacting around physical tools and artifacts[23, 24, 25] in service of design goals.

Thus, our model distinguishes communicating with others about your work, communicating about other's work (such as offering), and reading the research literature. Engineers must communicate about their own work and its value accurately, clearly, and succinctly to multiple audiences[26]. Not only must engineering apprentices learn to "speak like engineers" in the lab[22], they must also learn to write like scientists outside of the lab, communicating discipline-specific ideas to knowledgeable industry members, customers, community stakeholders, and engineers from a diverse range of disciplines, translating across a wide set of semiotic resources[23, 27]. Furthermore, researchers and practitioners alike increasingly recognize a need for engineers to learn to communicate with public audiences in a language unobscured by technical jargon[28]. Although, to date, few science or engineering education programs include instruction in such communication[29, 30], we argue for a need to include in undergraduates' engineering education, opportunities to experience and come to value communicating with publics through traditional genres (i.e., press releases, articles) and also through more informal, multimedia forms of communication that are arguably as important for scientific communication in the 21st century[31]. Thus, we integrated disciplinary writing not only as a writing-to-learn strategy, but also an engineering communication practice[34].

The ability to communicate about others' work includes not only practices associated with in-group collaboration in diverse teams and across projects[1], but also the ability to take up agentive audience roles[32] beyond one's own team. Practices associated with being a thoughtful, critical audience include evaluating arguments, offering critique, and connecting across projects during lab meetings and critique sessions that are common communicative events in engineering contexts[2]. Although reading the literature may at first seem tangential to communication practices, we argue from a literacy perspective, that reading is always a negotiation between authors and readers, and that the ability to apply ideas from published engineering research and other sources is critical to success in engineering fields.

Metacognition. Commonly defined as thinking about one's own thinking, metacognition refers to learners' reflective capacity to notice, direct, and sustain their cognition towards a goal, monitor the quality of their own performance and make judgments about how to improve[33].

Many scholars consider metacognition a critical engineering practice and have recommended fostering metacognition for engineering design process and team management activities[3].

Interdependence of practices. Finally, practices across the engineering processes model are interdependent and overlapping. For instance, in addition to being important in their own right, developing engineering communication practices allow novices to construct knowledge, identify with the domain, and navigate pathways towards collaborative engineering goals[35]. Further, communicating has been shown to facilitate metacognition[36]. Moreover, designing is interdependent with running tests and analyzing results because how a problem is initially framed impacts subsequent decisions and actions[3,7].

Embedding Community Building Elements

With the ERM in hand, we next turned attention to intentionally designing community building elements to support participation as outlined by Wenger[11] to help us purposefully embed engineering practices in the design of our REU program.

The REU community featured events such as shared meals, talks, and tours. Events were designed to allow students to interact with one another, and the wider engineering community. Leadership within this community was initially defined by two populations of leaders; one population of leaders was available to all undergraduates (program facilitators) and the other was available to undergraduates working on their specific project (project mentors). The community leaders who were available to mentor all undergraduate students included: Authors 4 and 5, engineers acting as general disciplinary mentors; and Authors 1, 2 and 3, educational researchers acting as a general community and learning mentors. We consider the seven research project mentors to be specific leaders in that they were engineers who mentored only two undergraduates through an engineering research project but had little interaction with the entire cohort of undergraduates.

Connectivity was promoted in two ways for our community. We set up a closed Facebook page for all of the research participants. To initially drive traffic to the page, we posted important documents and announcements there, but once the program started, participants drove the traffic to the page on their own. It became a place for them to ask questions, share information about solar engineering, and arrange social events. The second activity that fostered connectivity was that Author 2 and Author 1 acted to "broker relationships between people who need to talk or between people who need help and people who can offer help"[11](p. 232). Both program facilitators monitored participants' progress daily through 'checking in" conversations and through reading participants' daily reflections. When it was clear that participants were having difficulty these program facilitators made sure to connect participants to others who could help them. Additionally, other community elements like shared meals (events) fostered connectivity among students and with program staff.

Most learning projects in the program were designed around the research project, with the exception of the public communication project. We did not purposefully design community building elements around membership and artifacts as these were precisely defined either by NSF guidelines or the above practice model. One further note, we focus in this paper on engineering innovation and communication practices; metacognitive practices and the linkages among practices are beyond the scope of study.

Research Design

To understand the effects of our program design and implementation on students' belonging (engagement, alignment, and imagination/self-efficacy), we employ a single, revelatory case study approach[38] using mixed methods. As all of the authors participated in aspects of design and/or implementation of an REU focused on supporting various levels of participants through the experience, we hold the position of taking both emic and etic perspectives on program implementation. To better understand our program design and implementation as well as student outcomes around belonging, we ask the following questions:

1. How was the mode of imagination affected during the program?
    a. Which engineering research practices showed the most and least gains in self-efficacy across the program?
    b. What community building elements supported the mode of imagination?
2. To what extent did alignment to the practices change over the program?
3. How was the mode of engagement affected during the program?
    a. To what extent did participants engage in each engineering research practice?
    b. How did engagemen*t* happen for the most and least aligned practices and what community building elements were involved?

Context and Participants

The context of this study is a research experience for undergraduates (REU) program designed around the ERM model of engineering practices (See Figure 1 above). The study took place during a photovoltaic (PV) REU program at a large research university in the southwestern U.S. The REU lasted nine weeks during the summer and was a competitive, stipended apprenticeship. The program received over 200 applicants; fourteen were selected by a team of educational and engineering faculty. The selection criteria were developed based on NSF goals: broaden participation in engineering among women, underrepresented minorities, and veterans of the armed forces; include community college students to increase access to laboratory experiences; and nurture the development of students with the background and commitment to pursue engineering careers.

The REU participants included a diverse cohort of fourteen undergraduate participants from across the U.S. Participants represented a wide range of intersectional identities historically marginalized in engineering: six female, eight from underrepresented minority groups, seven from community colleges, and two veterans of the U.S. armed services. Appendix 1 displays demographic data about each participant.

Students selected for the program participated in two phases: Solar Cell 101 and Project Work. During the first two weeks, participants learned fundamental PV knowledge by manufacturing their own photovoltaic cells and using simulation software to design efficient cells (Solar Cell 101). For the remainder of the program, they worked in pairs (Project Work), with each pair working under one graduate student mentor on a separate engineering research project (7 projects total). In addition to the authentic research projects, the students participated in activities and events as a cohort throughout the program. Appendix 2 outlines the program events in detail.

Methods

REU participants completed regular surveys and reflections, including at the start of the program, the conclusion of Solar Cell 101, and at program's end. REU students also participated in pre- and post- interviews, as did their mentors. Furthermore, observations of program community events were conducted throughout the program by Authors 1, 2, 3, and 5 as participant observers[39]. Artifacts related to participation were collected, most notably for this study, teams' public communication projects, and final program posters. Additionally, a team of education graduate students aided with data collection efforts increasing the observations. The research team met bi-weekly during the program to discuss preliminary findings[40]. The following sections discuss the methods pertaining to each research question (RQ) in turn. Each RQ section includes details about data sources and data analysis. We used descriptive statistics to understand levels of modes of belonging and qualitative analysis to explain how those modes of belonging were supported and how they connect to community elements.

Data sources and analysis for Research Question One (imagination)

This mode of belonging includes participants' future vision of themselves with regards to the engineering CoP as well as their imagination of their current relationship to the CoP in the form of self-efficacy. Two data sources were used to operationalize participants imagination as a mode of belonging: pre-post administrations of a self-efficacy survey and post-program used to probe for how participants' saw themselves in relation to the CoP.

Self-efficacy. The self-efficacy measure focused on participants' imagined sense of their own current capabilities related to engineering. At two points in the program (pre and post), REU participants were asked to rate themselves on a scale from 0 (Completely Unconfident) to 100 (Completely Confident) with respect to their current level of self-efficacy or confidence for innovation and communication practices common across engineering and represented in the ERM. These question formats are generally accepted as valid measures for the types of knowledge or practice being assessed, within the limitation that rating scores reflect relative levels suitable for ranking or ordering rather than actual levels of the underlying knowledge or practice. Means and standard deviations were calculated for each of 15 items expressing enactments of each practice at both administration time points. Mean change scores were also calculated between pre and post responses on each item.

Interviews and written reflections. Participants were interviewed by a member of the research team at the beginning of the program, and again at program's end (only post-interviews were analyzed for the current study), and participants completed semi-daily written reflections throughout the program as part of engaging in metacognitive reflection on the engineering practices in which they were engaging. Although interviews and reflections were used to answer RQ1, they were relevant to RQ2 and RQ3 as well. We describe analysis in this section (RQ1) with the understanding that this data source and analysis are the same in the following sections.

Post interviews and written reflections were subject to qualitative content analysis using a priori codes[41].These codes were derived from the literature on designing CoP's[11] and include the modes of belonging (engagement, alignment, and imagination) as well as community elements (events, leadership, connectivity, membership, learning projects, and artifacts). Author 1 developed the initial codebook with definitions from the literature[39] and put those codes and the documents into the coding software, Dedoose. In the second step, Authors 1, 2, and 3 collectively refined the codes, systematically evaluating the utility of the initial code descriptions and the coders' ability to apply the codes consistently[42]. The second step was done by using two sample post-interviews for group coding in a series of coding meetings between the first three authors[40]. Group coding was accomplished through "dialogic intersubjectivity"[43] (p. 243), coming to complete consensus on the coding of the first two post-interviews. Using the refined code definitions developed during group coding, the first author then coded the remaining post-interviews and reflections, submitting that analysis to the second and third author as peer examiners and auditors to the coding process. Any concerns brought up about the coding of the remaining interviews and reflections were resolved through meeting and collectively coding contentious elements in the same process of complete consensus above[40].

Data sources and analyses for research question two (alignment). Alignment involves how well the participants were able to exhibit knowledge and skills of standard engineering practices congruent with PV engineering expectations and norms. Alignment here has been qualitatively determined by program staff based on performance measures, performance reviews, or artifacts produced by students. In addition to the interview data described above, analysis of participants' alignment involved two data sources.

ERM worksheet. Alignment with engineering practices was measured using an *ERM* alignment worksheet administered to all 14 participants on the first day of the program and again at program's end. The worksheet stands as a pre/post measure of students' knowledge of engineering research practices, asking participants to explain specific activities for each practice in Figure 1.

We compared each participant's pre/post response coding for positive change in understanding. Codes for positive change were defined as being able to explain a practice where they could not before, or explaining practices with a higher degree of specificity in the post survey. Each participant's responses to the engineering practices worksheet were coded and then quantified[43] for the pre/post measurement, and the percent of participants improved in each practice was calculated in order to infer change in knowledge that could be attributed to program participation.

Final research posters. All project pairs were required to create and present a research poster about their projects on the last day of the program during a poster presentation session. We treated these posters as artifacts that represent each project pairs' alignment to standard engineering concepts and practices. There were seven posters in all.

We conducted a qualitative content analysis[41] of the posters using our ERM practices to guide our coding. The first step of the coding process was to define the codes through the artifact[40]. This code development step took place over a series of eleven weekly meetings. During development, the first three authors looked at each poster, making analytic memos of information that could be gleaned from each poster and which ERM practices might be represented in the artifact. After looking at all seven posters we choose three posters to collectively code[40]. Collective coding of the posters relied on intensive group discussion around salient elements in the artifact and their relationship to the practices[40]. As a group, we reached "dialogic intersubjectivity"[44] (p. 243), coming to complete consensus on the coding of the first three posters. The first author then coded the remaining four posters and submitted that analysis to the second and third author as peer examiners and auditors to the coding process. Any concerns brought up about the coding of the last four posters were resolved through meeting and collectively coding contentious elements in the same process of complete consensus above[40].

As the posters were meant to reflect the aggregated alignment to practices of the participants as to understand the effect of the program, the final codes were quantified by magnitude for each practice (not present:0; low level of alignment: 1; medium level of alignment: 2; high level of alignment: 3) then averaged across all posters for each practice that was exemplified in the poster[43].

Data sources and analyses for research question three (engagement). For this mode of belonging, we relied on student reports of activities validated by observation. Engagement is simply the level of participation in each practice during the program.

ERM practices reflections. One set of written reflection questions relevant to the current study was a five-point, Likert-like self-report measure of how much time students spent engaged in each engineering innovation, communication, and metacognition practice as they worked with different community elements. This set of items was administered seven of the nine days during Solar Cell 101, the initial cohort activity in the program. During the last seven weeks, the Project Work portion of the REU, this set of items was administered at three time points, asking cumulatively about the previous week's activities regarding each practice.

Solar Cell 101 scores are over the seven days reported, we totaled the number of times each practice was reported as engaged in, and divided that total by the total number of positive and negative responses over the seven days. This gave us a descriptive percentage of engagement in each practice for seven days of Solar Cell 101. Since the Project Work ERM practice reflections were completed weekly, not daily as in Solar Cell 101, we calculated the total times each practice was reported engaged in that week, divided by the five working days to find the times/day each practice was reported all participants. Then we divided the times/day by the number of responses for that practice, giving us the percentage of engagement for each practice in each week reported.

Public communication projects. The fourteen participants were asked engage a public audience in any part of their work from the summer REU. Author 5 facilitated this project. The participants were given the open-ended task of translating some of the concepts or processes they were engaged during the REU into language for the general public and sharing their project with a public audience. Participants were also given the choice to work in groups or individually. Nine participants worked alone on their project, four participants worked in one group, and one participant worked in a pair with a visiting graduate student.

For the purposes of this study, analysis was limited to categorizing the projects as complete, partial or incomplete as a measure of engagement in the practice of communicating about my work with others (in this case, members of the public). Complete projects went through the entire process, from rough draft, feedback and editing to ending with a product that was shared with a public audience. Partial projects went through most of the process but did not share with a public audience. Incomplete projects did not move past the rough draft stage.

Integrative analysis. As a final step of analysis, we looked across the findings related to imagination, engagement, and alignment in order to understand the linkages among these modes of belonging for the REU participants. Data related to engagement was cross-referenced with data related to alignment, and imagination, which were also cross-referenced with each other, in order to explore their relationships. For the purposes of this study, we report here only the relationship between engagement and alignment. Specifically, we compared self-reports and observations of engagement to the scores measuring change in alignment in order to interpret what engagement looked like for the most and least changed engineering practices.

Findings

This section follows the structure of the section above with findings for each research question discussed in separate sub-sections.

Imagination

Research question 1a: How was the mode of *imagination* affected during the program? (a)Which practices showed the most and least gains in self-efficacy over the program? Operationalizing imagination in terms of self-efficacy allowed us a window into how participants perceived themselves as capable of full participation in the research practices of the engineering community. In terms of self-efficacy for engineering innovation practices (Figure 2), participants entered the program with low levels of imagination for themselves as community members capable of (a) generating ideas and designing solutions and (b) deciding what to try next based on analysis of results, activities represented as *design* practices in the EMR. These two practices, along with the high-level activity of synthesizing results from a variety of data analysis (Mean change = 18.46) also showed the highest Mean gain scores (i.e., 22.15 and 17.54) of the seven items representing innovation practices at program's end. Participants came into the program imagining themselves as fairly competent at practices related to *conducting experiments* and *analyzing results*, but still grew in their imagination of themselves as capable practitioners (Mean change = 16.92 and 11.38 respectively).

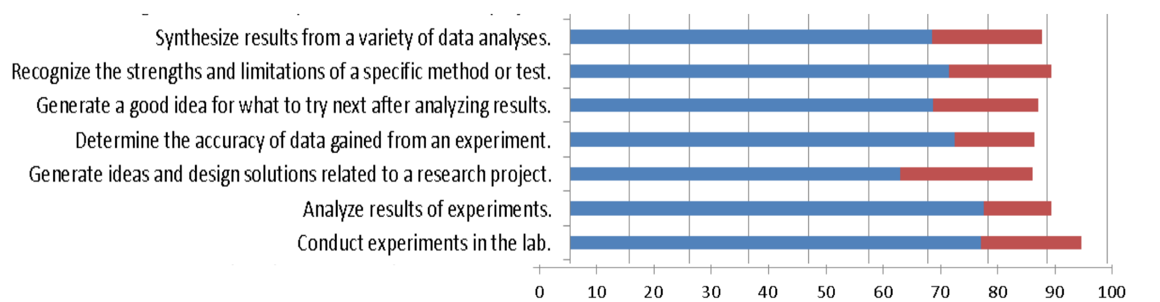

Figure 2. Pre-Post Mean REU Self-Efficacy for Engineering Innovation Practices (n=14). Pre-score means are represented in blue; post-score gains are in red.

Generally, relative to their self-efficacy for engineering innovation practices, participants entered the program with higher self-efficacy of engineering communication practices (Figure 3). Yet, pre-program mean scores on the nine items representing enactments of the three aspects of engineering communication practices also had a wider range, perhaps explaining why mean scores for these practices also saw a wider range of Mean change scores from pre- to post-survey administration than did the innovation practices scores. In particular, participants entered the program with relatively low imagination of themselves as capable of *communicating about their work to others*, including a range of audience types (i.e., peers, public, experts), but particularly for communicating with experts in the field. By program's end, mean scores on these practices were, in most cases, higher than post-mean scores for innovation practices, with the greatest gains in this set shown in communicating with peers (Mean change = 34.77), experts (Mean change = 34.31), and members of the public (Mean change = 18.77). Some of the highest pre-mean scores on the two items related to *reading the research literature*, though it is interesting to note that there is a mismatch between the self-efficacy scores related to this practice and measures of alignment (discussed below). That these scores showed little change by program's end (Mean Change = 5.23 and 8.31) corresponds with the relatively low levels of engagement we observed for this practice (discussed below). Finally, pre-program scores indicate that participants entered the program with low imagination of themselves as contributors to *communicating about other's work,* specifically giving critical feedback. This practice had one of the highest change score of all the practices (Mean change = 20), perhaps signaling the success of the weekly community event, lab meeting, in fostering a sense of belonging through imagination about self as contributor.

Participants entered with relatively high self-efficacy for reading the literature, which may explain low growth in this area. However, observations related to engagement and alignment suggest a mismatch.

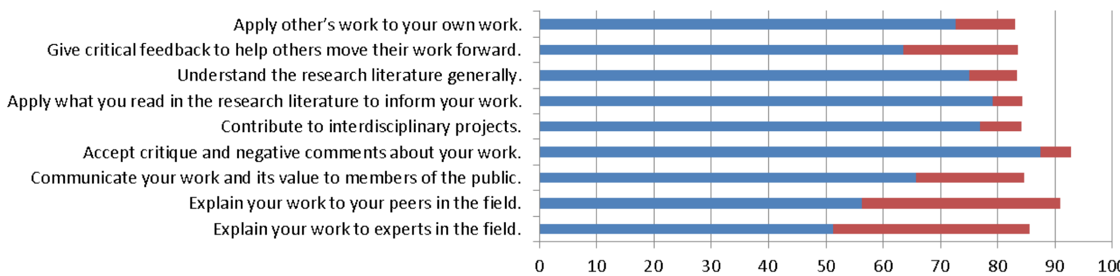

Figure 3. Pre-Post Mean REU Self-Efficacy for Engineering Communication Practices (n=14). Pre-score means are represented in blue; post-score gains are in red.

Research question 1b: In regards to RQ1b (What structural community elements supported the mode of imagination?), analysis of qualitative data shows that a combination of all community elements, with the exception of membership*,* supported students in imagining their future selves as engineers. In post-interviews, eleven of the fourteen participants expressed plans to pursue engineering as a career (imagining themselves as future engineers); four students specifically wished to pursue a graduate degree in PV engineering. One student explains:

> *I did not really consider a graduate program [before participating in this program]. I am just in my first year back at school so I have a long way to go and my intention was to go straight into industry, but now I am considering a graduate program and doing research as a possibility where I had not really even thought of it before…. I feel comfortable here. I feel like I fit in and I belong. I don't know, it feels great to be in this environment and I definitely want to continue working and become and engineer and now the possibility of doing research in a lab is there too instead of going to work for a company.*

This exemplary excerpt illustrates how the participant changed his imagination of his possible future self, based on a sense of belonging fostered by the REU.

The community element of leadership seemed to fuel the imagining of engineering futures seen above. In the post program interview, more than half of the students explained how they were supported or inspired by our program engineering staff. On student says of one of the engineering primary investigators (PI) that, *"He is a real inspiration"*. From observations, we know that the PI described above interacted frequently with all of the participants. He contributed to the mode of belonging of imagination by acting as an inspiring role model (leadership) and through the connectivity exhibited in his willingness "to give time to students".

Exposure to these leaders were intentionally designed for in the program through learning projects like the Friday lab meetings, where the entire cohort met and students would update their peer group on their research. Friday lab meetings were facilitated by engineering program staff, who provided feedback to students, guiding their research and answering questions.

Alignment

Research question two. We addressed RQ2 (To what extent did alignment to the practices change over the program?) through analysis of two data sources, each of which is addressed in turn. First, analysis of participants' pre-post scores on the ERM worksheet shows which practices were most improved across the cohort by program's end (Figure 4). This measure showed the most improvement in alignment of the practice *communicating about others' work* and least improvement in alignment with the practices of *reading the literature* and *design*.

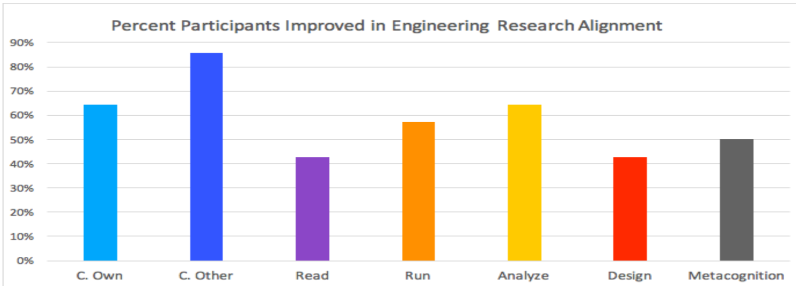

Figure 4. This graph shows the percent of participants improving in understanding of practices from pre to post-program using the ERM worksheet measure. The practices in the graph are color coded to match the practices on Figure 1. Abbreviated practices are: C. Own, communication about own work; C. Other, communication about others' work; Read, reading the literature; Run, run experiments; Analyze, analyze results. The color coding and the abbreviations remain constant across the following figures.

A second analysis looked in more detail at participants' alignment with engineering research practices as represented in their end-of-program poster (Figure 5). The poster was the end product of Project Work for each project pair. All ERM practices (Figure 1) were seen in the posters with the exception of communicate about others' work. Whereas our first measure of alignment was attending to pre/post improvement, in this measure we looked closely at the language, concepts, equations, graphs, and conventions exhibited in each poster and rated those with a rubric indicating the magnitude of each practice. A score of 0 indicated no evidence of that practice, 1 indicated low-levels of that practice, 2 indicated medium-levels of that practice, and 3 indicated high-levels of that practice. The rubric (coding scheme) was developed as described in the methods section above.

Poster analysis showed *running experiments* and *analysis of results* to be highly aligned across all project pairs.

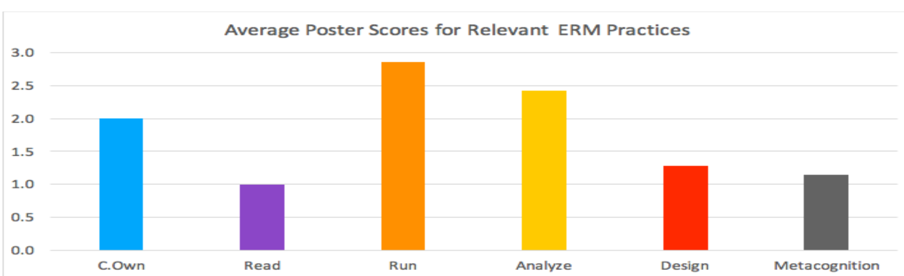

Figure 5. This graph shows the average scores across all participant's scores for each practice exhibited in the end-of-program poster artifact.

Across the two measures of alignment above, analyses consistently show that participants were least aligned with reading the literature and design throughout the program. The most aligned practices varied across these measures. However, overall, *communicating about one's* *own work* and *communicating about other's work* as well as *running experiments* and *analyzing results* all showed high levels of alignment in various measures.

Engagement

Research Question 3a: To what extent did participants engage in each practice? To understand how program design influenced engagement as a mode of belonging, we first examined participants' repeated responses to the relevant written reflection questions to investigate to what extent participants engaged in each engineering practice represented in the ERM during the two phases of the program, Solar Cell 101 and Project Work. Then we combined those responses to examine practice engagement across the total program (Figure 6) . Here engagement is operationalized as participation in each practice. High engagement in Figure 6 means that more participants were engaged in that practice at that time point. For example, looking at the Wk 1 PW block shows that almost 100% of the participants engaged in *reading the literature* each day (5 days) of that Project Work week. The blocks of Total Program and Total PW show the averages of the other blocks.

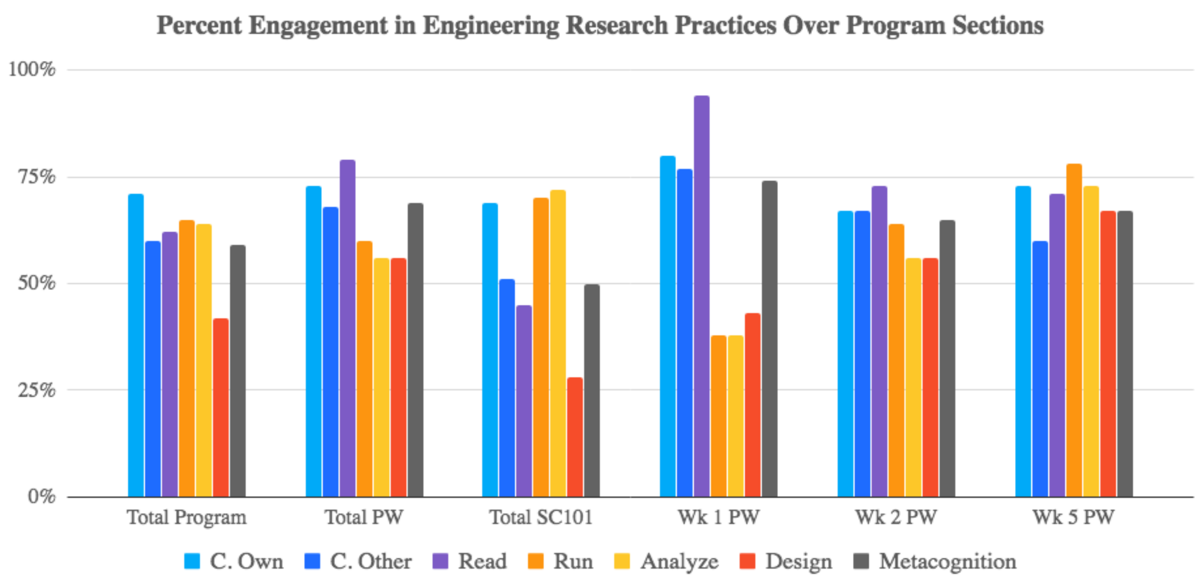

Figure 6. This graph shows the percent engagement in each engineering research practice over the course of the program. SC101 indicates Solar Cell 101, and PW indicates Project Work.

Looking first at the Solar Cell 101 phase, we see that running experiments and analyzing results show relatively high engagement. The Solar Cell 101 phase was designed to allow all participants to make a solar cell, analyze its efficiently, and take that solar cell home, so it is no surprise that run and analyze were highly engaged in as all the students were engaged in the same activities in this phase.

In the same Solar Cell 101 phase, we see that engagement in *communicating about one's own work* was also relatively high. Through observations and reflections, we found that cohort members communicated with one another often as well as communicated frequently with the mentors guiding the manufacturing process. This abundance of communication was made possible by the common task, common work space, and common working hours that the entire cohort shared for this phase of the program (cohorting).

Through the Project Work weeks, the innovation practices (*design, experiment, analyze*) increased across the three weeks measured, Week 1, Week 2, and Week 5. This is easily interpretable; at Week 1, these practice with regards to their project were new to the participants, and as they progressed through their projects these practices naturally increased. Contrarily, all three communication practices remained static or even decreased across the Project Work weeks (particularly in regard to *communicating about others work*). This is partially interpretable in regards to the very high level of engagement of all the engineering communication processes during Week 1. Additionally, during Week 1, most participants were observed working at the same times, and often in the same place, as they read the literature in preparation for their projects. As the project work progressed, we saw through observations and reflections that participants were isolated in their labs and had different work schedules revolving around experiment run times and instrument availability and location. In other words, as the Project Work weeks went one, the project pairs did not see each other as often as they did in Solar Cell 101 and Week 1 so communication was necessarily less.

The practice of *design* showed the least engagement. The section with findings around RQ3b will discuss data around this low engagement.

As a final analytic step in characterizing the extent of engagement for each practice, we examined participants' engagement in the Public Communication project. Of the 14 participants, all but two fully completed the Public Communication project, moving from framing a problem of interest for teaching the public about ideas they felt were central and useful to citizens at large, to drafting multiple iterations of multimodal texts, participating in critique sessions with peers, through to publishing their writing or videos on platforms and for audience members of their choice (See Evans & Jordan, 2019) for details and further analysis.

Research question 3b. How did engagement happen for the most and least aligned practices and what structural community elements were involved?

We were interested not only in which program community elements affected the mode of engagement, but also in how engagement was related to the other modes of belonging. In the following section, we limit our analysis to the relationship between engagement and alignment for the most and least aligned practices by program's end.. In addressing this question, we turn to qualitative analysis in order to illuminate the interdependencies between these two modes of belonging and the community elements.

Least aligned practices. These practices (reading and design) are discussed in detail below with regards to engagement and specific community elements.

Reading the literature. In the initial design of the REU program, we left support of reading journal articles wholly to the mentors to act as subject matter experts for each project. The education program staff found through daily reflections and observations that leadership in reading the literature and the understanding of the importance of reading literature to the field was highly variable among each project group. All undergraduate participants expressed struggling with the technical language and basic comprehension in either informal conversations with researchers or as part of their written reflections. This example is representative of the participants' experiences with reading:

> *My research partner and I were going through literature all day, and we would often discuss what we were learning. Quite often, neither of us had answers to the questions the other had.*

Although *reading the literature* showed relatively high engagement (Figure 6) throughout the program, it exhibited the least alignment in both the poster measure (Figure 5) and the ERM worksheet (Figure 4). The frequency of the sentiment expressed in the excerpt indicated that *reading the literature* was an exceptionally difficult task that required more support. The low alignment can, in part, be contributed to the lack of leadership that some project pairs experience in regards to this practice. Additionally, our program design did not include any cohort-wide events, learning projects or artifacts that may have supported participants in increasing their skill level with regard to reading the literature.

Through observations and reflections, the education program staff noticed the participants' frustration with reading; in response, program facilitators offered guided reading sessions. As this was mid-way through the seven-week project, only three students participated. One participant practiced guided reading on three separate occasions with program staff (not his project mentor) and when asked about his experience with reading the literature he explained:

> *It was really tough at first, I did not know- I guess the project was tough because when he (mentor) gave us the literature I did not know how to correlate it. But then as I went through the program, I learned how we use literature to kind of take bits and pieces from other research projects, other work and use all those ideas and those experiments to formulate our own research problem.*

This student and the two others who participated in extra reading support were among the few participants who articulated the link between reading the literature and the practice of design in research on the ERM worksheet indicating higher alignment to both practices. The extra reading sessions show how connectivity (the education staff's brokering of relationship in the form of tutoring) to leadership increased alignment to the practice of reading the literature.

Design. Although engagement in *design* increased over the program (Figure 6), design exhibited least engagement over the total program and was one of the least aligned practices in both the ERM worksheet (Figure 4) and the poster measure (Figure 5).

The Solar Cell 101 phase included a cohort-wide design learning project, PCD1 modelling, but engagement in design was relatively very low during that time (Figure 6). The project groups in the Solar Cell 101 phase were asked to design the most efficient solar cell they could using PC1D modeling software. We conducted an introductory demonstration and lecture at the beginning of Solar Cell 101, but most students still struggled with the basics of using the program indicating that this one event proved insufficient to support participants. Throughout Solar Cell 101, all participants wrote about the difficulty with that task in their reflections. *One student's reflection that, "the hardest thing we did today was to try to figure out how to model our given variable"* was echoed by all of the students

Only one of the students had ever used modeling software previous to the REU. When program staff noticed that the students were struggling they organized additional tutoring sessions around PC1D. Through observations, we saw that these tutoring sessions were focused primarily on using the software and less on understanding design.

During the bulk of the program (the Project Work), students' engineering research projects were originally designed by their mentors, and only one project pair was able to move through their project to a point where they could redesign. The bulk of *design* engagement for the rest of the pairs was only observed during our Friday lab meetings where presenters had to articulate their research questions and hypotheses justifying their experimental methods and analysis.

The timeframe of the projects may have kept students from high levels and meaningful practice of *design*. Additionally, the practice of *design* was left mostly to the supervision of individual project mentors as each project was very different, so levels of alignment to the practice of design showed higher variance from project pair to project pair. For example, one project pair indicated through the reflections that they engage in design most weeks while another project pair indicated that they never engaged in design during the project work.

Another possible explanation for low alignment to design lies in the relationship between *reading the literature* and *design* as seen in Figure 1. We submit that since they are linked practices, that the low alignment in reading may contribute to the low alignment we saw in design (Figures 4 and 5).

With regards to low alignment in design and community elements, there were fewer events, learning projects, and artifacts as well as less leadership and connectivity involved in supporting the design practice when compared to other, more highly aligned practices discussed in the following section. Also, since all participants were observed to struggle with *design*, connectivity with other students could not support higher alignment with *design* practices.

Most aligned practices. *Communicating about own and others' work* and *running experiments and analyzing results* all showed high alignment relative to the other practices (Figures 4 and 5). These practices are discussed in detail below with regards to their relationship with engagement and specific community elements.

Communicating about own and others' work. *Communicating about others' work* showed the highest improvement on the ERM worksheet (Figure 4) with 12 of the 14 participants showing improved understanding, but this practice was not as highly engaged (Figure 6) as the other high alignment practices. We submit that it was the novelty of this practice that contributed to its overwhelming improvement. Our initial workshop on presenter and audience roles, a learning project, stressed the importance of participating as a community member by communicating about others' work. In the daily reflections following the workshop more than half of the students commented that this workshop was the first time that they had received explicit instruction about audience roles. One student explains:

> *I also learned that as the audience, I need to make sure that I ask questions so that the presenter could move forward with their project. I also learned that it is not good feedback to just say that the presentation was "good" or "bad". Being specific about it and more critical about it helps more.*

Field notes show that many participants made similar comments during the workshop itself.

The practice of *communicating about others' work* was further developed by the ongoing engagement in the learning project, the Friday lab meetings, where we established a community norm that at least three students ask engineering questions and provide friendly, critical feedback after each presentation. Furthermore, all 14 students participated in giving critique to their cohort members through written feedback using a form designed for this purpose (artifact).

Communicating about one's own work was the most engaged practice in the program (Figure 6), but it showed lower alignment than communication about others' work (Figures 4 and 5). The program provided formal and informal supports for engagement in this practice. Friday lab meetings (learning project) and our workshop on audience and presenter roles formalized this practice. Additionally, a template (artifact) for the Friday Lab meetings was provided to guide students. Observations of Friday lab meetings indicate that all participants presented their research in-progress at least four times prior to the final poster session. In addition to Friday lab meetings, the poster event and the workshop preceding it represented the other set of formalized learning projects and artifact designed for communication about own work.

Formal workshops facilitated greater alignment. Many participants felt that the presentation workshop (learning project) was particularly valuable as seen in this reflection:

> *There were really good explanations about what we were doing, so this made everything a lot more clear. I was able to explain it to others because of the great explanations I received.*

Despite the successes of the intentionally designed elements for communication about own work, analysis of observational data suggests that, more often, engagement occurred as students communicated informally with one another about their own work, both within and across groups. We saw many comments in reflections like: *"I mostly used the other researchers who were in my [Solar Cell 101] group in order to gain more understanding and to employ ideas and get feedback."* It is noteworthy that this example exhibits alignment with the practice of *communicating about one's own work* in expressing that interaction with peers supported new understandings relevant for this participants' work.

All participants provided examples that *communicating about one's own work* occurred frequently and informally through the connectivity that students felt as a cohort. This connectivity was explicated by one participant during his post-interview when asked what events or relationships supported his participation in the REU:

> *I think that would go to all the other participants. Talking and seeing that we are all sharing similar experiences with our doubts on our projects, all running into kind of the same roadblocks and problems, just knowing that we are in this together even though we are all doing these different projects. It is all kind of a similar progression for REU student participants.*

Much engagement in the practice *communicating about one's own work* was supported by peers as opposed to more knowledgeable others like mentors and program staff, with mixed results for alignment. The following example is representative of positive alignment attributed to informally practicing communication about one's own work among the students, *"Working on our Friday PowerPoint presentation helped me learn. Student 1 explained to me a concept within our project which made things much clearer for me."* Through observations, reflections and interviews we saw that participants supported one another often in alignment through communication practices.

On the other hand, we saw many examples indicating that peer-to-peer communication supported alignment only to a certain extent. The following example illustrates the point:

> *My research partner and I spent two hours collaborating on the slides and discussed wording, structure, etc... My biggest concern so far about communicating the message is the art of dwindling down the intensive reading we have been doing to a five minute presentation. That is complicated to summarize. Especially because I don't understand it entirely.*

The above excerpt represents a common occurrence of peer-to-peer engagement in *communicating about one's own work*. Although engagement supports alignment, in this case, there was a limit to that support. One reason *communicating about own work* may have had mixed results for alignment, with many participants failing to use the canonical language in their posters, is that engagement often occurred through peer-to-peer interactions as opposed to interaction with more expert CoP members. The excerpts above show that some communicating with peers offers support of alignment, but other aspects of alignment need the support of mentors and program staff.

Occasionally, informal events like meals promoted connectivity that increased alignment to the practice of *communicating about their own work*, as in this example:

Mentor 1 helped student 2 and I with the PowerPoint presentation by giving us feedback … [He] offered advice....We did not know how to do that so he showed us and that was a huge help.

In this example, mentor 1 was not the pair's formal project mentor, he was a mentor that they become connected to during Solar Cell 101. Although this was not a rare occurrence, we saw this type of interaction less frequently than peer-to-peer interactions.

The excerpts above indicate that working on the PowerPoint presentations, a community element of artifact, required for the community learning project of the Friday lab meeting spurred engagement and alignment in communication of students' own work with peers and leadership (mentor 1). Further, this community engagement was also facilitated by the community elements of connectivity and events. Despite the high engagement in *communicating about their own work* (Figure 6), on average, participants performed at a medium level by the end of the program (Figure 5). This outcome suggests that more involvement from engineering leadership may be needed to accompany the copious peer-to-peer opportunities for communicating about their own work.

Running experiments and analyzing results. Opportunities for participants to engage in the engineering innovation practices of *running experiments* and *analyzing results* were present in both Solar Cell 101 and in Project Work. During Solar Cell 101, all students ran the same experiments and did the same types of analysis. During Project Work, project pairs participated in highly varied experimental procedures and analysis.

During Solar Cell 101, connectivity among the cohort, with the program staff and the seventeen Solar Cell 101 mentors was supported by the common task as well as the common space and time of the experience. All of the students, mentors, and staff were present either in the conference room or in the lab from about eight in the morning to four in the afternoon during this part of the program, and since the entire cohort of students was working on the same tasks peers were able to help one another which we observed frequently. This cohort-wide learning project provided a platform for the high engagement in *running experiments* and *analyzing results* (Figure 6, SC101 group). The mentors were cited by all participants as extremely helpful during Solar Cell 101 with regards to alignment of these two practices. The following example was common in reflections:

When my group needed to do QE measurements, [mentor 1] was the one that led us…. Because there were two steps for the calibration, one for the wavelength range of 300nm - 1100nm, and one for 1110nm-1200nm. She did the 300-1100 range first, and from watching, I did the second range. During the calibration, she explained what the machine did.

This participant went on for ten more lines, giving a detailed and accurate explanation of quantum efficiency (QE), how it was measured, and how it related to their project. This example and abundant similar examples show that the learning project of solar cell fabrication, the solar cell as an artifact, the connectivity with different members of leadership culminated in both high engagement and high alignment of *running experiments* and *analyzing results*.

During Project Work, Figure 6 shows the trend of week one having low engagement in run and analyze, but ramping up as the weeks progressed, ending with relatively high engagement overall. We observed that some pairs were engaged in *running experiments* followed by *analyzing results* almost daily throughout the Project Work while other pairs were not. This variance depended upon the specific project. For example, three project pairs had to wait to use certain instruments that were being repaired or were reserved. Some project pairs were using instruments that required lots of training while other project pairs were using instruments that were easier to master. After project Week 1, we did observe that all project pairs were running experiments and analyzing at least three times a week. By the end of the program all project pairs were able to use the instruments specific to their projects and articulate why that instrument was important. Many participants were able to discuss, in depth, the technical aspects of running experiments, as exemplified here:

> *My project is about characterizing Indium-Oxide (IO) which is a Transparent-Conductive-Oxide used to allow holes to pass through the amorphous-silicon layer into the metal contacts and also serves as an anti-reflective coating layer. So now by characterizing, we need to deposit IO on glass to determine what the right thickness, carrier mobility and carrier concentration are.*

This participant continues to discuss the intricacies of each experiment needed in technical detail in 15 more lines. All of the participants, when discussing their experiments, could articulate their work with canonical language and concepts, which we saw on the final posters as high alignment to *running experiments* (Figure 5).

Analyzing results also showed relatively high alignment through our analysis of participants' final posters. *Analyzing results* and *running experiments* during Project Work were left solely to the project mentors and occasionally the primary investigators (PI's) of their lab. Although interactions with the PI in the labs were rare across project pairs, when it did occur, we saw that it was a highly positive experience with regards to supporting alignment with running experiments and analyzing results. One participant said of the PI of her lab:

> *Dr. One was awesome!!!!! She is inspiring. We discussed attending weekly group meetings, Discussed lifetime –vs- injection curves that are affected by one main limiting defect, Effective lifetime = 1/teff= (1/tsrh+ 1/taug+ 1/trad)bulk+ 1/tsurf…..*

The above participant continues to elaborate a lengthy and accurate reflection about *running experiments* and *analyzing results*. Only three project pairs ever met with their PI's, but each time they experienced this type of connectivity, they exhibited a similar clarity, direction and excitement seen in the excerpt above. Most of the time we observed mentors with project pairs they were engaged in running experiments and analyzing results. Although most mentors were consistently available to their project pairs, we also observed three project pairs experience a lack of connectivity. In one instance, a project pair waited an entire day to learn how to use and instrument, but their mentor never showed up. Another project pair expressed frustration with the lack of a definite schedule of meetings, they said that they often had to "track their mentor down". The third pair was just observed alone, without their mentor, about three days a week while some mentors spent several hours with their mentees every day.

Running experiments and *analyzing results* formed the bulk of engagement between project mentors and project pairs; these practices were additionally supported by a variety of mentors in the cohort-wide learning project of Solar Cell 101. There was engagement between peers here also, the project pairs, but, in contrast to the communication practices, these two practices were overwhelmingly supported by more expert members of the CoP with high results for alignment in these practices during Project Work and Solar Cell 101.

Discussion

Being highly invested in the success of novice engineers, many from populations underrepresented in engineering and many traversing engineering research pathways for the first time, our team of educational researchers and engineering researchers set out to design a summer

REU that would scaffold newcomers into the profession by supporting their sense of belonging to the program and to engineering more broadly. Analysis of data generated during the first implementation of the design indicates that participants' sense of belonging was supported by a program designed around embedded community elements based on a CoP framework, and the reification and embedded use of an explicit model of the innovation and communication practices common to the engineering research process, i.e. the ERM. In the following discussion, we expand on the meaning of this success, its limitations, and the implications for practice in engineering apprenticeships for cohorts of undergraduate students, particularly cohorts purposefully aimed at supporting students from populations historically under-served and underrepresented in engineering.

Our findings suggest that strongly framing and intentionally designing a research experience for undergraduates (REU) supports students' belonging in an engineering community of practice. The collaborative work of an interdisciplinary team of engineering and education researchers was essential to the design and implementation of the REU. During program design, education research experts brought strong theoretical framing in the form of the theory of CoP's[10] and designing for CoP's[11] while engineering research experts brought specific and detailed knowledge of core community practices. This collaborative design work culminated in the ERM (Figure 1) and the program outline (Table 2). Likewise, implementation of the program was supported by the continued collaboration of this interdisciplinary team, with educational researcher carefully monitoring participants' modes of belonging in real-time and engineering researchers responding with extra support.

Generally, our results suggest high alignment was achieved by participants in engineering research practices that were supported by more than one community element while lower aligned practices did not have as many community elements supporting them. When a combination of artifacts, events, leadership, connectivity and learning practices supported a practice, on average, undergraduates showed higher alignment. In other words, a variety of community elements better supports newcomers' capacity building or alignment to the practices. We saw this with both elements of the ERM, *communicating about one's own work* and *communicating about others' work*. As negative cases, both *reading the literature* and *design* had the least variety of support and manifest the least alignment.

We additionally saw that distributed leadership supported alignment of engineering research practices. When students could rely on a variety of mentors and facilitators for a practice, they showed higher alignment. Peer support, as part of distributed leadership, was also found to be helpful in practice alignment. We contend that the distributed leadership including peer support may have been effective through providing more opportunities for engagement of the practices. We also note that peer support, while providing much opportunity for engagement, works best when all of the students were exposed to other elements prior to peer engagement. For example, it was difficult for peers to aid other peers in reading the literature and design as our program provided less support for the cohort as a whole.

We argue that the strong cohort experience of Solar Cell 101provided the foundation for increased alignment through peer support. For example, in Solar Cell 101(learning project), the practice of *running experiments* was supported by diverse and distributed leadership, an artifact (e.g., the final solar cell that participants took home), connectivity (e.g., compressed time and space of the project), events (e.g., shared meals and lectures), and expanded membership (e.g., cohort-wide project). During Project Work, *running experiments* was further supported by high connectivity between high-level leadership (e.g., mentors and PI's) and high levels of engagement (e.g., participants ran the same experiments several times). Contrast this support with that of *reading the literature*. In the initial program design, we left support of participants' reading the literature to a single leader (i.e., each pair's project mentor) due to the highly specific nature of the papers that were assigned for each particular project. We did not provide an artifact, such as a checklist or tips sheet to guide the reading process or application of an article's content to the participants' research projects, and we did not organize cohort-wide specific learning projects or events around this practice, such as a reading workshop or collective study of a shared reading. We have some evidence, through the guided reading sessions (learning projects) in which three participants engaged with Author 1, that distributing the leadership helped participating students align with this practice. With these examples in mind, we suggest that providing more avenues of access to each practice will support students' alignment. These avenues should include access to different and diverse leaders (distributed leadership), as well as access to supporting artifacts and formal learning projects dedicated to the development of each specific practice.

Strong program design requires strong theoretical grounding, and we submit that Wenger's[11] theory of designing CoP's provides a valuable foundation to program design of REU's. For one, the idealized characteristics, processes, and functions of REU programs are well represented as apprenticeships within a CoP. Additionally, Wenger offers specific, actionable community elements that support newcomer integration. REU participants are newcomers not only to the research programs to which they are apprenticed, but also to the larger community of engineering within the specified discipline. Our program is an example of using strong theoretical underpinnings in the intentional design of a program for newcomers, particularly newcomers who are vulnerable to leaving engineering education and career pathways due in large part to not having a sense of belonging[15]. Finally, Wenger[11] presents a more complex conceptual model of belonging than does self-efficacy measures alone. We suggest that engineering education scholars might benefit from further consideration of what the construct of self-efficacy means and what it points at or signals with respect to participants' imagination of themselves relative to a community, as a community member or a potential community member.

We propose that future REU programs use a model like the ERM as a theoretically grounded framework for guiding the design of structural supports that foster a sense of belonging. We also submit that cohorting and partner pairs add the important community element of connectivity and opportunity for distributed leadership that allows lower-level students access to help from their peers. We believe that no practice should be left to one form of leadership alone (e.g. project mentors only), in other words an REU program should employ a distributed leadership model with regards to all practices they wish to support. Another point of design of program involves careful planning of learning projects to include artifacts. We also encourage interdisciplinarity among the design team, particularly having both education and engineering program staff as part of design and implementation.

Limitations and Directions for Future Work

Although our current paper introduces, operationalizes and analyzes all three modes of belonging in a CoP, we believe that the modes of imagination, engagement and alignment are more interdependent than the scope of our paper would allow us to describe. Similarly, the practices as expressed through the arrows on our ERM model are interdependent, but we only describe linkages for some in this study.

We saw indications in our study, but we have not systematically analyzed here the limitations of graduate students mentoring low-level undergraduates through the experience. We believe that mentors faced as many challenges as did the undergraduates as they juggled their own dissertation projects while mentoring. Time pressures, lack of experience with mentoring best practices, and no pay may have contributed to less accessibility for some project pairs. Further analysis needs to explore the role graduate student mentors play, and what community structural elements can be put in place to support these important members of the CoP.

Future studies need to closely examine the dynamics of learning through participation in engineering apprenticeships as a CoP, for instance, by analyzing the way the practice of engineering communication, in formal and informal contexts, and through various and interdependent mediums (e.g., slidedecks presented at weekly lab meetings, and oral discourse) changed over time. Additionally, as indicated by the ERM model, future studies also need to look at metacognition and linkages among practices. Finally, the findings of this study are limited in that they were based on analysis conducted at the group level. Rich comparative case studies would shed more light on the dynamics of the CoP as a social learning system.

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Appendix 1. Participant Demographics

Name	Major	College Level	GPA	Ethnicity	Gender	1st Generation
MIC 069	Environmental Science	Senior	3.22	-	F	-
KAN 503	Electrical Engineering	Sophomore (Community College, CC)	3.96	Hispanic	F	Yes
PAM 461	Engineering	Sophomore, CC	4.0	Caucasian	M	Yes
PIE 959	Environmental Studies	Junior	3.54	Caucasian	F	Yes
ANG 504	Electrical Engineering	Junior	3.94	Hispanic	M	-
SYE 571	Engineering	Sophomore	3.32	Middle Eastern	F	No
MAR 365	Electrical Engineering	Senior	3.83	Caucasian	M	No
ISH 697	Civil Engineering	Sophomore, CC	3.92	Native Hawaiian	F	Yes
JOL 639	Mechanical Engineering	Sophomore, CC	3.103	Hispanic/African America	M	No
TAT 071	Environmental Science	Sophomore, CC	3.93	Asian	M	-
KAT 435	Biology	Freshman		Asian	F	No
ELI 565	Computer Science	Sophomore, CC		Caucasian	M	No
MIC 620	Engineering	Sophomore, CC		Caucasian	M	Yes
SHA 758	Engineering	Freshman, CC		Caucasian	M	No

Appendix 2. Program Events

Program Element	Time/Duration	Led By	Purpose	Community Element Types (Wenger, 2000)
Pre-program reading	Sent pre-program and used throughout.		To allow students to acquaint themselves with the basic science concepts around PV engineering. To introduce them to a resource they could refer to during their research.	Artifact
Orientation Day	Day 1	Program Staff	Introduction to program staff and the program elements and expectations.	Event with leadership
What is Research? Talk		Engineering Program Staff	To broadly introduce the purpose of research and set expectations of the experience.	Event with leadership
Introduction of the Engineering Research Model(ERM)		Education Program Staff	To introduce the students to the organizing model of activities and events we used to design the program.	Event with artifact and leadership
Getting to Know You BINGO		Education Program Staff	To introduce students to one another and program staff and foster a sense of belonging.	Event with connectivity
Reflection on the ERM		Education Program Staff	To allow students to write down their conceptions of the activities that are involved in each of the model's sections. This also served as a pre-test of their general knowledge around these areas for themselves and for the staff. It helped to orient our workshops and other activities.	Learning project with artifact
Introduction to PV Engineering		Engineering Program Staff	To introduce students to the main concepts underlying PV engineering. This allowed them to ask questions.	Event with leadership
Design Thinking Workshop		Education Program Staff	To introduce students to collaborative problem solving outside of the context of PV. To engage student in the process of collaborative design.	Learning project with connectivity
Solar Cell 101 (phase 1)	7 Days (after orientation)	Various graduate student mentors	To introduce the cohort to the solar cell manufacturing process and allow them to create a solar cell that they could keep.	Learning Project with artifact, connectivity, leadership, and membership
Assigned to 3-person groups	Throughout Solar 101	Assigned by program leaders	So that they could work as a team.	Membership with connectivity

Lab Work	Throughout Solar 101	Various graduate student mentors	Introduce the cohort to the equipment and procedures in the making of a solar cell.	Learning Project with artifact, connectivity, and leadership
PCD1 Modeling	Throughout Solar 101	Engineering Program Staff	To introduce students to elements of design and solar cell efficiency. To use the down time of lab work wisely, and to engage all students in a shared, collaborative task.	Learning project with connectivity and leadership
Presenter and Audience Roles Workshop	One hour during Solar 101	Education Program Staff	Introduce students to best practices and expectations of audience members contributing to the work of their peers.	Learning project with artifact and leadership
Group Presentation	Last day of Solar 101	Program staff	Allow students to reflect and communicate on their work during Solar 101 to include the making of solar cells and PCD1 modeling.	Learning Project with artifact
Project Work (phase 2)	7-weeks after Solar 101	Project Mentor	To provide an authentic research experience for the students. Allow students to both learn and contribute to the community	Learning Project with leadership
Assigned Project Pairs	Throughout the Project Work	Program Staff	To allow pairs support through the project. To encourage collaborative problem solving.	Membership and connectivity
Project Mentor Introduction	1 hour meeting with mentor after Solar Cell 101	Project mentor	To introduce pairs to their mentor and project and allow for questions.	Event with connectivity and leadership
Assigned Reading for the Project	At the beginning of the project work	Project Mentor	To give the new researchers relevant journal article to their projects and introduce them to technical reading	Learning project
Lab work	Throughout the Project	Project Mentor	To support the research project and introduce students to new instruments and methods.	Learning Project with leadership
Breakfast and Lunches	Throughout the entire program	Program Staff	To encourage cohort social engagement. To allow for moments of celebration and community news. To cut down on time students had to search for places to eat. To connect students with other mentors and PI's.	Event with connectivity and leadership.
Guest Speakers	Throughout the entire program, usually once a week	Various guest experts in engineering	To introduce students to the breadth of work around PV engineering. To allow students to network.	Event with connectivity and leadership
Field Trips	Throughout the entire	Various sites related to	To introduce students to industry	Event with connectivity and

	program	PV engineering		leadership
Public Engagement Project	4 weeks from the last week of Solar 101 to the end of our first month.	Education Program Staff	To introduce students to translating engineering work for the general public. To allow student to reflect on their work in a different manner. To encourage students to think about the societal implications of their work.	Learning Project with artifact and connectivity
REU Friday Lab Meetings	Throughout the program after Solar 101	Engineering Program Staff	To allow students to reflect and communicate their projects to their peers under the guidance of an engineer.	Learning Project with leadership, artifacts and connectivity
Writing Workshop	Two hours towards the end of the program	Engineering Program Staff	To introduce students to the practice of engineering writing focused on their final poster presentation.	Learning Project with leadership
LinkedIn Talk	One hour toward program's end	Engineering Program Staff	To introduce students to digital networking.	Event with leadership
Facebook Page	Throughout the program	Education Program Staff	To allow students to network easily. This was a closed page and served to make official announcements. Later participants used it to organize social outings.	Connectivity with membership
Poster Session	Last Day of the Program	Program Staff	To allow students to present their work to a larger audience in an authentic engineering poster session format.	Learning project with artifact