

Fostering Multi-Institutional Collaboration in Engineering Research Centers: An Analysis through the Lens of Communities of Practice*

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An effective Community of Practice (CoP) enhances the professional development of student trainees and their work performance. Although efforts have been made towards fostering CoP in the engineering fields, there is still a need to improve students' social learning experiences in the context of the United States' Engineering Research Centers (ERCs). The goal of this study is to provide practical implications for researchers and program managers to strengthen and improve ERC operations. Using qualitative research methods, this study investigates the experiences of ERC members, including faculty, students, postdoctoral researchers, and staff members, to understand how collaboration and knowledge exchange are facilitated across institutional boundaries. The findings reveal that motivation for work, regular meetings, project-based collaboration, and dissemination activities are critical mechanisms for sustaining engagement and momentum in the center. The study also highlights that community and practice aspects of the ERC need improvements in order to resemble features of CoP. This study has practical implications for ERC educators and leaders to make deliberate efforts to standardize protocols and better integrate members from diverse backgrounds, which may foster a more efficient and inclusive CoP. These findings offer valuable recommendations for ERC leadership to strengthen collaborative research and organizational performance.

Keywords: engineering research center; multi-institutional collaboration; interdisciplinary research; organizational performance; Communities of Practice

1. Introduction

In the United States, Engineering Research Centers (ERCs) are organizations dedicated to maximizing the societal benefits of engineering and encouraging participation in the field. With funding provided by the United States National Science Foundation (NSF), 75 ERCs have been operated by multiple research universities since 1985 [1]. Currently, there are 19 active ERCs, each with a defined research project, and the goals of these organizations are twofold: first, to support university collaboration, in which the convergence of science, technology, and education creates a positive societal impact, and second, to broaden the participation of talent in STEM fields. It is evident from these goals that every ERC goes beyond its research project to promote the development of engineering workforces at all stages of participation, foster an environment of mutual benefit among participants, and generate value in an innovation ecosystem that will sustain itself even after the funds for an ERC expire, generally, in ten years [2].

To achieve these goals, ERCs incorporate members from multiple universities and industries, such that synergies are maximized and learning outcomes are improved. Students in the center include undergraduate students, graduate students, and postdoctoral researchers. They are the main work-

force in ERCs and are offered opportunities to gain a deeper understanding of their field by closely working with their faculty members and by collaborating with faculty members and peer students outside their participating labs. Prior work suggests that interdisciplinary engineering collaboration within and outside of ERC participants' technical backgrounds increases satisfaction and learning outcomes [3–5]. As a result of such interdisciplinary engineering collaboration and research participation, students build confidence in becoming professionals in the field [6] and crystallize their post-graduation career goals [7].

Moreover, graduate students in ERCs are key players in producing research and generating knowledge. With the guidance and supervision of their faculty advisors, students commonly run experiments and write reports on their findings and progress. They also take on responsibilities to mentor undergraduate students in their research experience [8]. In addition to these roles, students in ERCs present their research to colleagues at other participating universities and companies. As a result of this knowledge exchange process, faculty and students identify gaps in their understanding of the project's scope and tasks and address concerns that occasionally arise in multi-institutional projects that may otherwise go unaddressed.

In such a multi-institutional project, commu-

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nities may form to promote collaboration and education, particularly in the field of engineering, which emphasizes problem-based learning and practice-based application [9, 10]. According to Henri and Pudelko [11], four types of communities can be classified according to their characteristics: communities of interests, goal-oriented communities, learners' communities, and communities of practice. The differences between these communities are characterized by the sense of membership and their purpose of gathering. In some cases, these inherent characteristics of a community evolve, possibly leading to the transformation of that community into something else. For example, Communities of Interest (CoI) are characterized by shared passions, hobbies, or interests that bind individuals together. These communities provide a forum for like-minded individuals to connect, share experiences, and engage in discussions around common topics of interest. Goal-oriented communities are formed around specific objectives, tasks, or projects, with members collaborating to achieve shared goals. These communities are characterized by a collective commitment to achieving desired outcomes within a defined timeframe. Learners' communities are centered around the pursuit of knowledge, skill development, and continuous learning. These communities provide a supportive environment wherein individuals can engage in collaborative learning activities, share insights, and seek feedback from peers and mentors.

The term Communities of Practice (CoP) was coined by Lave and Wenger [12], and they propose that members of CoP share a vision, build social bonds by meeting regularly, and cultivate professional identity. Lave and Wenger [12] developed the concept of CoP to explain and understand the process by which professional communities introduce and educate new members, and the ways in which they sustain established procedures for completing specific tasks. From their perspective, CoP is not an ideal to achieve in an organization but a reality that is organically fostered within. Nonetheless, of the four different types of communities, the strongest social bond amongst members is fostered in CoP, where members gather with a specific goal in mind at an individual and collective level. The development of strong social bonds in CoP occurs because CoP encourages learning to be a social process that requires active participation and interaction with others rather than just acquiring knowledge and cognitive skills. In CoP, knowledge is perceived as a dynamic resource, finding its fullest value when actively applied in real-world scenarios and shared with others, stimulating progress and empowering individuals and communities alike. As a result of participating in such social

learning activities, aspiring engineering students, for instance, build motivation to develop a new social identity as engineers that enhances their sense of inclusion in the community [13]. Unsurprisingly, as a result of its strengths in simultaneous interplay between learning and socialization, a strand of literature suggests that the best teams form CoP [12, 14, 15].

As described above, ERCs may organically evolve into communities; however, in order to enhance student trainees' professional development and work performance, an effective CoP has to be fostered. Although efforts have been made to foster CoP in engineering fields [16–18], there is still a need to enrich researchers' and program managers' ideas on how to encourage ERCs across the country to operate better and more efficiently. Therefore, this study aims to uncover the functional mechanisms of ERCs using the framework of CoP by looking at how the three components of CoP (i.e., domain, community, and practice), are operationalized in an ERC.

Guided by this overarching objective, this study poses two research questions:

- (1) What are the key mechanisms underlying the functioning of the ERC examined in this study, and how do they contribute to multi-institutional research and practice?
- (2) To what extent does the ERC operate in accordance with the principles of communities of practice?

Through a comprehensive exploration of these questions, this study seeks not only to enrich our understanding of ERC dynamics but also to pave the way for ERC leadership to foster a community of practice within their organization, which in turn may have numerous organizational and individual benefits.

2. Literature Review

The concept of CoP is often used, and has proven influential, in engineering fields and the broader Science, Technology, Engineering, and Mathematics (STEM) community. CoP is frequently cited and discussed in examinations of an individual's experiences in classes, degree programs, and departments [13, 16]. The CoP concept was originally developed for assessing and improving practice-based organizations, such as profit-making companies [12], and it has been used in the engineering industry for assessing organizational effectiveness and performance [19, 20]. As researchers have increasingly recognized the benefits of social learning, they have modified and utilized the CoP concept in diverse engineering settings, including

research groups, schools, and informal learning environments [21–23]. These strands of work continue to offer valuable insights for educators to apply in analyzing the current engineering classroom and fostering a stronger engineering community [4, 24, 25].

Despite the benefits of using the CoP framework for improving the efficiency of engineering projects, there have only been a few studies that have examined the ways in which CoP can be utilized in multi-institutional research projects [26]. The concept of CoP has been used by researchers from multiple universities as a theoretical construct for incorporating the multidisciplinary knowledge and experience of various stakeholders into solving societal problems and supporting scientific advancements [7, 27]. In particular, this study highlights the use of CoP in engineering research collaboration, which leads to generating teams that assemble individuals with talents and expertise and creating a collaborative environment where members can utilize their disciplinary and professional knowledge to address complex challenges [27]. This study also suggests that, by engaging in regular meetings and exchanging knowledge, team members enhance their comprehension of each other's areas of expertise, recognize opportunities for collaboration, and create inventive solutions that go beyond the limitations of individual disciplines.

2.1 Theoretical Framework: Communities of Practice

In order to identify similarities between an organization and the CoP concept, the elements of CoP should be used. These elements consist of three interconnected components: domain, community, and practice [12]. Each of these components has a crucial role in influencing the work environment and operations of the community.

The term '*domain of CoP*' refers to the broad field of knowledge or expertise that unites its members [12]. The domain helps the members define their identity and identify the main issues and difficulties that they aim to tackle. The domain, such as collective objectives, interests, and concerns, brings people together in a community, creating a basis for working together and sharing information. Within the context of an ERC, the domain encompasses specific areas of study, research subjects, or technological aspects that serve as the foundation for collaborative investigation and invention. The domain establishes the base for expertise and research, creating a sense of belonging and unity among community members. In this way, the domain sets a threshold for directing the combined efforts of the members towards achieving a common goal.

The *community* aspect of CoP refers to the group of people who are associated with one another through their shared involvement in a particular field and interpersonal interactions [12]. It captures the interconnectedness of the community, consisting of many individuals and organizations such as students, corporations, and research collaborators. The community forms a bond through which individuals connect with one another, exchange knowledge, and work together to solve shared problems. Members offer their distinct viewpoints and expertise to promote shared learning and progress. Such a community in an ERC may facilitate cross-disciplinary exchanges and foster lasting professional relationships within a community that includes numerous universities and industries. By consistently participating and communicating, members of ERCs that function as CoP may foster a feeling of trust and friendship, enhancing the social connections that are the foundation of cooperative efforts.

The *practice* aspect of CoP refers to the collective set of tools, techniques, and methodologies that define how the community tackles problem-solving and knowledge generation [12]. This concept includes the implicit knowledge, most effective methods, and established rules that direct the actions of members and broaden their professional identity within the community. Practices within an ERC may encompass a range of activities, such as research methodologies, experimental techniques, data analysis frameworks, and project management strategies, among others. Through active participation in communal activities, the members may enhance their abilities, broaden their knowledge, and make valuable contributions to the collective knowledge in their field. Furthermore, the practice aspect acts as a stimulant for lifelong learning and creativity as participants adjust and improve their methods in responding to changing difficulties and possibilities.

In addition to the three theoretical components, artifacts in the CoP framework represent the tangible products, documents, tools, and technologies developed by the members over time. In engineering disciplines, these might include design specifications, engineering models, simulation tools, technical reports, and class assignments. When developing artifacts, engineering students can showcase their competence and contribute to the shared practice of the community. As an example, earlier research found that when engineering students participated in service-learning projects, they were able to produce tangible outputs like affordable housing designs for Habitat for Humanity that not only served the community but also improved students' ability to share a common goal

and work collaboratively [28]. Also, artifacts may include communication channels the community establishes through which members of the community exchange information [29]. These artifacts can facilitate knowledge exchange and community building and help CoP establish and strengthen a shared repertoire of resources.

There are a multitude of benefits to using the CoP framework; however, only a few studies have looked closely at how organizations operate in accordance with the CoP framework while promoting community building and team effectiveness. Much research is still needed to provide the basis for recommendations that can inform the practice of researchers working in multi-institutional centers such as ERCs. The findings of this study address the gap in how CoP can be used as a guide to improve an ERC's performance and strengthen multi-institutional collaboration and research.

3. Methods

This study employed the qualitative single case study approach developed by Yin [30]. This approach enabled the researchers to explore common experiences and perceptions of ERC members in their learning and collaboration opportunities. In this study, the ERC served as a case in which the members' insights and perceptions of their experiences were explored and analyzed. The analysis focused on identifying commonalities between the units (participants) in order to generate a holistic understanding of the ERC community dynamic [30].

3.1 Unit of Data Collection

In this study, we examined 23 participants' experiences and perceptions of their work and relationships. The 23 participants were the sources of evidence for observations about the ERC's community dynamic; Yin [30] identifies them as the units of data collection. These participants are selected for this study because they not only agreed to participate in the full study but also actively engage in the daily activities and operations of the ERC and thus provide rich insights into the collaborative dynamics within the community.

Using convenience sampling [31], we recruited participants who could provide a basis for a holistic understanding of ERC operations from a range of ERC members with varying career stages, membership durations, and *project groups*. The ERC of this study is a multi-institutional collaboration involving three lead institutions, with its center located in the Northeastern United States. The focus of this ERC is on advancing engineering science through interdisciplinary research and innovation. The term

project groups is used in this study to indicate groups of members who work in the same division within the project, share common sub-goals, and contribute as a team to the larger organizational goals. These members often share disciplinary backgrounds (e.g., material science engineering or biomedical engineering) and use similar equipment and tools (e.g., 3D scanning printers), but may work in different geographical locations.

3.2 Data Collection

Yin [30] suggests that collecting multiple sources of data for a qualitative case study is key to gaining a holistic understanding of phenomena of interest. In this study, a pre-interview survey, a semi-structured interview, and observational notes were used. To collect data, a recruitment email was sent out to the members at the ERC via their email provided in the center's listserv.

The recruitment email contained a link to participate in a pre-interview survey that asked for the respondent's demographic information and about their experiences at the center. A total of 24 participants agreed to participate in the study and completed the survey, but one withdrew due to scheduling conflicts. Before the participants proceeded to the semi-structured interview, the survey responses were reviewed and incorporated into the interview protocol, which will be further discussed in the next section. Prior to all data collection, the researchers obtained approval from the Institutional Review Board to ensure that the study conformed to ethical standards.

Participants who completed the pre-interview survey and had agreed to participate in the remainder of the study were invited for the interview. The interviews were conducted over Zoom and lasted around 60 minutes. As a result of the recruitment effort, a total of 23 individual interviews were conducted with the ERC members. The members included nine students, four postdoctoral researchers, seven faculty members, and three staff members, as shown in Table 1. As the ERC was in its sixth year of operation when data was collected, participants could have worked there for a maximum of six years. Study participants' gender and race are not disclosed in this study in order to protect their confidentiality. In addition, gender-neutral pseudonyms are used to protect their identity.

3.2.1 Pre-interview Survey

Prior to the interview, survey responses (e.g., "*How many years has it been since you were a member of ERC?*" and "*Who do you identify as your mentor?*") helped provide a general sense of the participants' experiences at the ERC, such as their current

Table 1. Participants

Occupation	Pseudonym	Years at the Center	Project Group
Student (9)	Riley	1	A
	Avery	2	C
	Emerson	2	C
	Taylor	1	C
	Sawyer	1	C
	Ryan	5	A
	Parker	5	A & B
	Kai	3	A
	Rowan	3	A & B
Postdoc (4)	Quinn	3	C
	Blake	2	B
	Morgan	2	B & C
	Cameron	5	A
Faculty (7)	Robin	6	B & C
	Charlie	6	C
	Alexis	5	A & B
	Rick	6	B
	Peyton	4	C & D
	Dylan	1	C
	Frankie	3	C
Staff (3)	Logan	5	D
	Bailey	5	D
	Sage	5	D

relationships with colleagues and the duration of their membership, and enabled the researcher to tailor interview questions and thus gain a deeper understanding (e.g., *I noticed from your survey response that you work closely with Logan. What are your key communication channels or tools?*).

3.2.2 Interview Protocol

The interview protocol was designed to elicit insights on the participants' experiences and perceptions of the ERC community, their roles and interactions, and the overall work dynamics at the ERC. For example, the interview questionnaires included prompts such as, *"Please briefly tell me a little bit about your responsibilities and tasks in your current position."*, *"Which aspects of your job do you consider to be most important?"*, and *"What has kept you motivated to continue doing your job?"*. These questions focused on understanding the participants' perceived primary roles at the ERC and their motivations for the work. Also, participants were asked to reflect on their experiences of collaborating with other team members and the challenges they may have faced in doing so. For instance, questions such as *"What has been your experience working with ERC members to complete the job?"*, *"Has your experience working with ERC members at other institutions or labs changed over time?"*, and *"What has been successful in working*

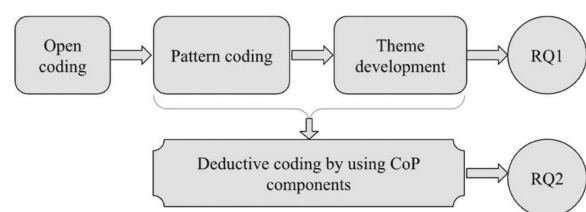
with ERC members?" were asked of participants. Lastly, to gain a better understanding of the means and methods for collaborative work at ERC, a question about the artifacts they used to facilitate collaboration was included: *"If any, what types of materials or tools do you use to collaborate and communicate with ERC members?"*. This question allowed participants to give examples of any relevant artifacts that they used in their collaborative experiences, such as communication channels, that could provide additional context for their responses [32].

The interview responses elicited by asking the questions as described above constituted the primary material for analysis; however, observational notes generated by the primary researcher and the pre-interview survey responses were also used to supplement the interview data. This was helpful because, as ERC members themselves, the researchers were able to participate in the general meetings and engage with the members at the center, as insiders of the study phenomenon [33], as is further discussed in the positionality of researchers section. These types of interactions and participation increased the researchers' understanding of the overall mission of the ERC and team dynamics at the center.

3.3 Data Analysis

The analysis for addressing the first research question involved three steps: open coding to develop a preliminary codebook, creating categories that encapsulate similar patterns observed in the codes, and identifying themes [30], as shown in Fig. 1. First, the primary researcher conducted open coding to identify concepts and relationships that initially emerged as important. In this process, interview transcripts were reviewed along with audio recordings simultaneously to capture audible signals, such as hesitation and emphasis [34]. The observation notes taken before and after the interviews were also used to supplement the data and flesh out the picture of the participants' experiences.

After open coding, we moved on to consolidating the codes into categories. This process of categorizing the data allowed the researchers to identify patterns that were observed in the codes. For

**Fig. 1.** Analytic process.

example, a category emerged when repeated use of codes referring to communication means (e.g., *email*, *Zoom*, *Slack*, *annual site visit meetings*, and *community retreats*) appeared in the data. These codes were grouped into the single category of *hybrid communication channels* to show a pattern of typical social interaction.

Then, themes were developed to capture the meaning, role, and experience associated with the categories. This process included comparing and synthesizing categories to identify participants' most common experiences in descriptive clauses, rather than in short labels [35]. For example, it became evident through examination of the category *hybrid communication channels* that other categories, such as *sense of belonging*, *sense of community*, and *engagement*, needed to be incorporated to capture participants' full experiences of using these communication channels and their role(s) in the ERC. These latter categories were adjacent to the former category, which helped draw a holistic picture of participants' experiences and identify key mechanisms of ERC's operations. As a result of the theme development process, *Regular meetings maintain momentum and engagement* was identified as one theme that addresses the first research question of this study.

To address the second research question, we took one more analytic step, deductive coding. This is a qualitative analytic approach to examining data with a theoretical lens or predefined understanding of phenomena of interest [31]. In this study, the CoP components were used to deductively examine the extent to which the ERC operates in accordance with it. The CoP theory suggests that domain must comprise broad fields of knowledge; community must encompass shared involvement, interconnectedness of community, and an open environment for knowledge sharing; practice must include a collective set of tools, techniques, and methodologies; and artifacts must present well-defined products developed or used by the members [12]. Using the examples and definitions of the CoP concepts, the categories and themes developed in the previous step were revisited to classify them into relevant concepts. It is important to note that these were not mutually exclusive. For example, a theme, *Regular meetings maintain momentum and engagement*, which comprised categories of *hybrid communication channels*, *sense of community*, *sense of belonging*, and *engagement*, was deductively analyzed and classified as *artifacts*, *practice*, and *community* because the members' use of such channels helped improve their productivity and engagement. This step was essential for identifying overlaps and key organizational features that mirror the functioning of CoP.

3.4 Trustworthiness of the Findings

According to Lincoln and Guba [36], triangulation is an essential strategy for ensuring the credibility of qualitative research. Triangulation can be accomplished through various means; in this study, the researchers utilized multiple data sources (e.g., interview transcripts, observational notes before and after each interview, to provide a pre-interview survey) and a thick description of participants' input. These three sources of data were triangulated to gain a full understanding of participants' experiences, for example, utilizing participants' survey responses to ask follow-up questions during the interview (e.g., "*I noted that you were involved in this center for about three years! Do you believe the ways you communicate or collaborate with others in the center has changed over time?*"). Observational notes were also used to gain a contextual understanding of the participants' experiences, such as meeting environment and team culture.

3.5 Positionality of Researchers

The researcher who conducted the interviews is also a member of the ERC. This gave the researcher an insider's perspective and a deeper understanding of the ERC community. Although such an insider perspective may produce some level of bias, the researchers in this study meticulously reflected on their positions working on educational research and professional development at the ERC and sought to provide recommendations on areas for improvements in community dynamics. The researchers in this study have expertise in engineering workforce development research and share a passion for improving the inclusivity of the environment for all members at the center, which motivated them to conduct this study.

4. Results

This paper focused on a single ERC as a case to better elucidate the dynamics and operations of the center and provide a basis for improving its operations. To achieve this goal, this paper used CoP as a theoretical lens to assess the extent to which the ERC operates as a CoP.

4.1 Context

For the reader to gain a broader comprehension of the selected ERC, a contextual understanding of the ERC research topic can be helpful. The ERC has a mission of creating advanced metamaterials inspired by biological systems through an interdisciplinary approach that blends materials science, biology, and engineering. The center's research focuses on designing materials with unique proper-

ties, such as self-healing and adaptive capabilities, by understanding and applying cellular and metabolic processes. The ERC aims to address real-world challenges with these innovative materials, with potential applications in medicine, environmental sustainability, and advanced manufacturing. By leveraging the processes of biological systems, the ERC seeks to transform material science and create solutions with significant societal impacts through multi-institutional research collaboration and innovative approaches.

To address the first research question, a qualitative analysis was conducted to identify the key mechanisms of the ERC's work operations. The findings showed that the key mechanisms underlying the ERC's operations are *motivation for work, dissemination activities, regular meetings, and project-based collaboration*.

4.2 Key Mechanisms Underlying the ERC Operations

4.2.1 Motivation Comes from Different Sources, but Different Motivations Share the Same Direction

The members do not necessarily enter the ERC with the same motivation for work, as they come from various backgrounds. For example, Dr. Blake is a postdoctoral researcher, and Parker is a PhD student, and they had different motivations that influenced them to join the ERC. Dr. Blake stated, "Part of the reason I wanted to come here [the ERC] was to have a platform to learn [skills and knowledge in electrical properties], and part of it was also to explore my interests in the lab." In contrast, Parker said,

"I didn't really have much experience with specifically [specialty] engineering. What I did know when I came into graduate school is that I wanted to use biomaterial systems and engineer cell tissue culture platforms to understand biological processes and tissue regeneration generally. So, when I came into the lab, Dr. Alexis, my principal investigator, had this project that Dr. Alexis had just gotten some funding on because Dr. Alexis just joined the ERC and said, 'Here's this project that I think would be a really good fit for you. I know you don't know anything about this [specialty] thing, but would you be interested?' And I said yes."

While Parker joined the ERC solely because their principal investigator recognized Parker's interests in the field and had funding available for them to work on the ERC research project, Dr. Blake's primary motivation was a desire to develop expertise and enhance their skills. The two members' expectations at the center differed because they had different motivations for joining the ERC. Because Parker explored their research interests

relevant to the ERC, their expectation was more geared towards crystalizing their passion and gaining exposure. Dr. Blake's expectations were more specific and targeted to achieve a set of goals through the ERC experience, such as gaining electrical engineering skills and knowledge. Although their expectations and motives differed, the ERC provided a platform for them to work together, learning from and mentoring each other and building a community for professional development.

The faculty members, in contrast to the students and postdocs, expressed motivation to join the ERC because they identified areas for students' professional development and opportunities for interdisciplinary collaboration. Dr. Rick, for instance, stated:

"What motivates me is to see students succeed in this kind of environment. And for other principal investigators to grow and succeed in directions that they were perhaps not working on before they joined the team. So, the sense of having an environment that allows people to thrive [and] seeing them succeed is one of the things that gives me a lot of pride and energy."

Dr. Dylan also added that the opportunity for interdisciplinary collaboration and innovation motivated them to join the ERC, saying,

"I believe that a significant portion of the effort being driven by the ERC involves addressing numerous questions and challenges . . . If we can contribute a piece to that effort, that's really kind of stimulating. That keeps my interest and involvement, both with my colleagues at [my university] and with the broader ERC group. There's a lot of people doing interesting stuff, and it's brought up new collaborations and extended how we could maybe use some of the things we're doing and opened up doors for new data that we could help analyze and work with. That's really what keeps the motivation going."

As stated above, participation in the ERC further helped the faculty members expand their professional networks.

Staff members also found the ERC to be a rewarding workplace, and the work aligns with their values of training students through practical research and outreach activities. For example, Logan said,

"I generally tell people I really enjoy what I do, mainly because I love helping high school students in summer research programs and graduate students at the ERC and watching them grow through the program. So that's what motivates me – just to ensure that my students are motivated to continue to grow."

Participants goals to make broader impacts and support the ERC's mission are key drivers for their engagement. Despite the differences among subgroups, all members reported that the ERC offered them opportunities to make broad and positive

impacts on professional development through research activities and collaboration.

4.2.2 Dissemination Activity Functions to Form a Community

Disseminating their research findings to both academic and non-academic communities is one of the primary goals of ERC members. For example, ERC members participate in dissemination activity by publishing research papers and patents, presenting at conferences, and organizing workshops and public events. Amongst the members, faculty, staff, postdocs, and most students actively participated in disseminating technical research activities, like Dr. Quinn. Dr. Quinn actively collaborated with ERC colleagues at various labs and locations and stated that the team was close to publishing results. “My colleagues are working a lot on the ERC [specialty products]. We have several models for collaborations on publications, conference papers, and journal papers.” Staff members also worked on disseminating findings on their activities related to engineering community building and outreach programs. For example, Dr. Sage created an engagement kit in collaboration with science museums to help them communicate the ERC research to K-12 students and provide exposure to engineering and science fields. “[I created a space for] the graduate students or postdocs [to work] with science museums to share what the ERC research is like. And then together they brainstorm ideas for how it can look like an activity. And I think it winds up being a mentoring process.” Although the audiences for these dissemination activities may differ, dissemination activities constituted one of the primary goals, unifying the members as a community to achieve the ERC’s overall mission.

When the members of the ERC get together for preparation of dissemination activities, such as center-wide retreats and site visits, it provides an opportunity for them to share their work, seek feedback, and engage in stimulating discussions. One student, Taylor, said that in such meetings, they may not necessarily work on the same projects, but they can always learn from each other’s work and get new ideas to apply to their own research. Taylor said,

“[A professor from a collaborating university] was talking about this system they were creating. He said [...] that they were never able to recreate [an aspect of the research worked] because you have certain [phases and cycles] and that’s different [...]. [To my surprise,] I [had] just read a paper suggesting that, [something different was occurring on the system]. I was like, ‘That can be possible.’ First, I’ve never talked with him before, but I was like, ‘Professor, I read this paper you might find it interesting.’ He said, ‘Oh, okay, send

it to me,’ and he began working on this project. That was just because I come from more of a [...] mechanics type of world, so I read different papers than just this [specialty], so I have different information, right? I found that that was super cool. I literally just was reading a paper that was useful for my other research, and that was helpful for them!”

These types of interactions served as helpful avenues both for identifying potential research ideas and collaborative opportunities in areas they had not previously imagined and for the reinforcement of collaborative, interdisciplinary community.

4.2.3 Regular Meetings Maintain Momentum and Engagement

In addition to the dissemination activities, regular meetings were another key mechanism that contribute to the functioning of the ERC. The ERC regularly organized several meetings, workshops, and annual events to share research progress, discuss emerging issues, and explore potential collaborations. For example, community meetings were held virtually every month to debrief on members’ accomplishments and plans to promote a sense of belonging and engagement. Journal clubs were another virtual avenue for students to discuss scientific journals in order to broaden as well as deepen their understanding of interdisciplinary fields. In addition, site visits, retreats, and industry days offered the ERC members an opportunity to meet physically every year and participate in events that are designed for various stakeholders in the project (e.g., NSF program managers and evaluators, and industry professionals). Participants highlighted that these meetings were instrumental in maintaining momentum and commitment among the ERC members. Dr. Charlie mentioned, “We have very regular meetings, and these meetings are [...] a lot of technical meetings, which, in my opinion, were very helpful to keep people together in terms of identifying their common goals.” Dr. Rick also added that,

“Both the retreats and the site visits every year, each time we meet, improve the interaction of our team even more. Because then everybody hears, maybe that’s another form of communication that everybody then hears and sort of forms a collective vision for what the program is.”

Sawyer and Rowan also emphasized that these regular meetings help to keep everyone feeling “a sense of community” and understanding of how each member’s activities are well-aligned with the ERC’s strategic goals. These responses indicate that regular meetings create an environment for the members to build professional relationships and strengthen their momentum towards achieving a collective goal of the ERC.

4.2.4 *Project-based Collaboration Serves as a Driving Force for Multi-institutional Research and Innovation*

The ERC's emphasis on project-based collaboration is another key mechanism that underpins its operations. Participants noted that the center's research projects entail interdisciplinary teamwork and understanding of the team's expertise. For instance, Dr. Frankie described an incident when project-based collaboration opened an opportunity to advance in computational methods, saying,

"I think that the thing that I'm most excited about coming from my group has been being able to put out computational methods or sort of do things in a way that wouldn't have been possible if we didn't have the experimental collaborators at the ERC. [We] basically applied a method to three different platforms and had all these students that had undergrads and PIs involved. That definitely wouldn't have existed without the ERC, so that was exciting."

This example indicates that project-based collaboration invites members to be interested, excited, and engaged. In such collaborations, faculty members and their lab members can take on parts of the project that they couldn't do on their own.

However, such project-based collaboration also presents some challenges, such as a lack of availability. For example, Rowan stated that while project-based collaboration is the best way to engage everyone in research and drive progress, the projects often faced challenges in coordinating everyone's availability, particularly when students were already occupied with other responsibilities unrelated to the ERC: "If there are competing priorities and a trainee has other commitments to other work that is not related to the ERC, I wouldn't say it's difficult, but there's a different level of wanting to be engaged, and there's only so much I can ask of another individual."

Nonetheless, participants appreciated the benefits of project-based collaboration despite the challenges, as it fosters a sense of shared purpose, mutual learning, and collective problem-solving among the ERC members. Therefore, providing these opportunities through project-based collaboration encouraged multi-institutional research and innovation, which served as a key mechanism for running the ERC.

4.3 *Comparative Characteristics of ERC and CoP*

The findings related to the second research question highlight the extent to which the ERC aligns with the principles of CoP. The analysis reveals that while the ERC demonstrates a strong foundation in the domain aspect of the framework, there are notable gaps in the community and practice dimensions.

4.3.1 *Domain: Strong Collaborative Research through Interdisciplinary Expertise and Technological Innovation*

The ERC encompasses a broad domain characterized by diverse expertise across multiple engineering disciplines, such as mechanical and material science engineering. This breadth of knowledge fosters an environment conducive to research collaboration, enabling members to pursue collective objectives effectively. Furthermore, faculty members demonstrated a strong commitment to student learning and development, and students identified opportunities to align their professional aspirations with personal goals. This alignment not only enhanced collaborative research efforts and students' identities as learners but also generated an environment of shared purpose among faculty members and students.

Technological sharing emerged as a pivotal element in facilitating collaboration within the center. Zoom was a mutually agreed-upon communication platform, along with emails, Slack, and the center's website, has made resource sharing and information exchange efficient in a multi-institutional setting. This multifaceted approach to communication underscores the center's commitment to fostering a collaborative research environment.

4.3.2 *Community: Mixed Experiences of Participation and Engagement in the Collaboration*

The community aspect of the center is partly aligned with CoP concepts, particularly regarding shared involvement and interconnectedness among members. Regular meetings, including the Trainees Leadership Council and journal clubs, play a critical role in promoting student engagement and facilitating collaborative initiatives. Additionally, opportunities for project-based interactions further enhanced interconnectedness, allowing members to work together on shared objectives.

However, some participants expressed a desire for more accessible and efficient collaboration methods, particularly concerning engagement with members outside their immediate labs. This feedback suggests a potential area for improvement in fostering a more cohesive community. In terms of creating an inclusive environment, faculty members' proactive efforts to ensure student involvement were identified as key drivers. Their accessibility and open communication significantly contributed to a culture of inclusivity, where students felt empowered to engage actively. Students also highlighted the importance of developing a safe environment, such that asking questions during technical meetings was encouraged and judgment-free for fostering an inclusive atmosphere. Some

students also reported experiencing ambiguity regarding their roles in projects and expressed concerns about inadequate onboarding support. Students' perceptions and experiences of feeling unsupported during the onboarding process and insufficiently included in meetings indicate that the center's community aspect of the framework has yet to meet its full potential.

4.3.3 Practice: Hits and Misses in Effectively Individualized Lab-by-Lab Research Procedures

The practice aspect of the ERC revealed mixed outcomes. While all members acknowledged research dissemination and collaboration as primary objectives and main activities, a lack of universally accepted tools and techniques was identified. This absence of a common framework impeded the collective efficacy of collaborative efforts. Even though there were efforts to create a standard way of coding and using the same program software, these projects ran into problems because members showed a reluctance to accommodate the change in each lab's current programming mechanism. This made it harder to set up a common framework for making experiments more repeatable and analysis more consistent. Despite the challenges, all members expressed satisfaction at succeeding in publication and dissemination in various journals with state-of-the-art research findings.

Overall, the findings indicate that the ERC demonstrates a strong foundation aligned with the CoP framework, particularly in its domain dimension. However, enhancements are necessary in the areas of role clarity, onboarding support, and the development of shared practices to fully leverage the center's collaborative potential. In its current state, the ERC greatly resembles a goal-oriented community where participants share a common goal and are engaged in collective activities; however it lacks some of the core elements of a CoP. Therefore, future efforts should focus on addressing these gaps to foster a more effective and inclusive research environment.

5. Discussion and Implications

The findings of this study have several implications for leaders and faculty members at an ERC. This study found that the current ERC operates more like a goal-oriented community. A goal-oriented community is under pressure from outside forces to achieve a specific objective within a given period of time [11]. Under the supervision and evaluation of NSF, successful ERCs should produce numerous high-quality papers, patents, and grant proposals, and this study found that the participant experience indicates this is indeed the case, which, as the

analysis shows, corresponds to the characteristics of a goal-oriented research community. While the CoP is widely recognized as the organizational model that most successfully fosters social learning, builds members' strong sense of community, and facilitates high performance, Lave and Wenger [12] suggested such communities should not be enforced nor should they be conceived as a model to emulate. Rather, this article makes valuable recommendations for ERC leaders to reinforce their core functions through which members, especially the students, may work efficiently and collaboratively.

First, ERC leaders might focus on cultivating a learning-centered approach rather than merely pursuing a goal-oriented agenda. While having a clear goal undoubtedly helps students to perform tasks, the ERC should offer them sufficient opportunities to engage in active and collaborative learning. Particularly when students are onboarded to the ERC project, receiving adequate resources to fully understand the center's goal and gaining opportunities to attend social events are critical for their close engagement and learning. This study also found that members have various motivations for joining the ERC. Prior studies suggest that individuals reflect upon, re-identify, align, and strengthen their motivations by engaging with others and understanding their motives [37, 38]. Therefore, the ERC can improve students' learning by encouraging their participation in social events that are not always focused on technical subjects but also those that are more geared toward professional development and networking.

Second, while the virtual communication platforms partake in the role of community building, in-person meetings might improve their focus on students' social learning. This study found that site visits, annual retreats, and industry day were few in-person gatherings where the members interact physically and meet people outside of their on-going project groups. Although the ERC regularly offers such in-person events, these events can be enhanced further by incorporating more interactive and collaborative activities. For example, the annual retreat could include an ice-breaking session for new students, a panel discussion with alumni members discussing their career pathways, and a group-based activity where students from different institutions work on a specific challenge. The emphasis on interpersonal relationship building, generating new ideas, and fostering ownership of work should be placed on par with technical sessions, as suggested by previous research [39–41].

Lastly, the ERC could benefit from implementing standardized technical platforms and research protocols across its various projects. Although project-based collaboration was found to be a very effective

means of promoting multi-institutional collaboration, this study identified some challenges. Due to the non-permanent nature of the project, a lack of using a common technical platform or computing language hindered fluid translation of collaborative research protocols. The ERC excels in employing diverse expertise across various fields, but each expert tends to rely on their own methods and tools for conducting research, making it challenging to integrate their work into a shared pipeline. While research can still progress and yield successful outcomes, the ERC could significantly enhance its productivity by developing and adopting a common platform or standardized protocols for its multi-institutional projects.

This study makes novel contributions to ERC primary investigators as well as engineering educators to better understand how an ERC can strategically shape its structure, programs, and activities by helping them foster meaningful learning and professional development among its students. By incorporating the recommendations from this study, ERC leaders can create an inclusive and collaborative learning environment that supports students' academic and career aspirations.

This study is not without any limitations. This study explored participants' experiences during the summer in the sixth year of the ERC, which might have illustrated a limited perspective on the overall development of the center. Future research might employ a longitudinal study to fully assess the transformation of the ERC over its full duration, which may provide key insights for the strategic planning of the center.

6. Conclusion

This study emphasizes the importance of cultivating an effective CoP in order to enhance the professional development and performance of student trainees within the U.S. ERCs. Using qualitative research, this study examined the experiences of faculty, students, postdoctoral researchers, and staff members in order to identify key mechanisms underlying the functioning of the ERC. These key mechanisms include motivated work, regular meetings, project-based collaboration, and dissemination activities. Additionally, comparing these key mechanisms with the CoP, this study identifies opportunities for improvement, particularly in the area of integrating and standardizing protocols to create a more efficient and inclusive community. These findings provide practical recommendations for ERC leadership to enhance collaborative research and organizational performance.

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References

1. National Science Foundation (NSF), "ENG – Engineering Research Center (ERC) | NSF - National Science Foundation." <https://www.nsf.gov/eng/eec/erc.jsp>, Accessed: 25 March 2024.
2. National Science Foundation (NSF), "About the Division of Engineering Education and Centers | NSF – National Science Foundation." <https://www.nsf.gov/eng/eec/about.jsp>, Accessed: 9 April 2024.
3. T. Brower, M. Knight and C. Rogers, Undergraduate research: teaming engineers with non engineers, *2005 ASEE Annual Conference*, pp. 10.1369.1–10.1369.11. Portland, Oregon, USA, 12–15 June 2005.
4. R. G. Hadgraft and A. Kolmos, Emerging learning environments in engineering education, *Australasian Journal of Engineering Education*, **25**(1), pp. 3–16, 2020.
5. R. Komarek, A. R. Bielefeldt and D. W. Knight, Influences of Engineering Students' College Experiences on Leadership Skill Assurance, *International Journal of Engineering Education*, **37**(5), pp. 1454–1465, 2021.
6. B. Hemmings, Sources of research confidence for early career academics: a qualitative study, *Higher Education Research & Development*, **31**(2), pp. 171–184, 2012.
7. E. Odera, A. J. Lamm, L. C. Odera, M. Duryea and J. Davis, Understanding how research experiences foster undergraduate research skill development and influence stem career choice, *NACTA Journal*, **59**(3), pp. 180–188, 2015.
8. B. Ahn and M. F. Cox, Knowledge, skills, and attributes of graduate student and postdoctoral mentors in undergraduate research settings, *Journal of Engineering Education*, **105**(4), pp. 605–629, 2016.
9. L. Mann, R. Chang, S. Chandrasekaran, A. Coddington, S. Daniel, E. Cook, E. Crossin, B. Cosson, J. Turner, A. Mazzurco, J. Dohaney, T. O'Hanlon, J. Pickering, S. Walker, F. Maclean and T. D. Smith, From problem-based learning to practice-based education: a framework for shaping future engineers, *European Journal of Engineering Education*, **46**(1), pp. 27–47, 2021.
10. National Academy of Engineering, *Understanding the Educational and Career Pathways of Engineers*, National Academies Press, Washington, DC, USA, 2018.
11. F. Henri and B. Pudelko, Understanding and analysing activity and learning in virtual communities, *Computer Assisted Learning*, **19**(4), pp. 474–487, 2003.

12. J. Lave and E. Wenger, *Situated Learning: Legitimate Peripheral Participation*. Cambridge University Press, New York, NY, USA, 1991.
13. B. E. Hughes W. J. Schell, B. Tallman, T. Sybesma, M. B. Kwapisz, E. Annand, S. Ranch, C. Krejci, C. Bozic and D. Kotys-Schwartz, Entering the community of practice: changes in engineering students' engineering identities and perceptions of the field, *European Journal of Engineering Education*, **46**(6), pp. 968–986, 2021.
14. J. S. Brown and P. Duguid, Organizational learning and communities-of-practice: toward a unified view of working, learning, and innovation, *Organization Science*, **2**(1), pp. 40–57, 1991.
15. I. Pyrko, V. Dörfler and C. Eden, Thinking together: What makes Communities of Practice work?, *Human Relations*, **70**(4), pp. 389–409, 2017.
16. B. Diaz, C. Delgado, K. Han and C. Lynch, Use of communities of practice to analyze and improve graduate engineering education, *2022 ASEE Annual Conference*, Minneapolis, MN, USA, 26–29 June 2022.
17. S. Fincher and J. Tenenberg, Using theory to inform capacity-building: bootstrapping communities of practice in computer science education research, *Journal of Engineering Education*, **95**(4), pp. 265–277, 2006.
18. S. Ma, G. L. Herman, M. West, J. Tomkin and J. Mestre, Studying STEM faculty communities of practice through social network analysis, *The Journal of Higher Education*, **90**(5), pp. 773–799, 2019.
19. A. Schenkel and R. Teigland, Improved organizational performance through communities of practice, *Journal of Knowledge Management*, **12**(1), pp. 106–118, 2008.
20. J. Wanberg, A. Javernick-Will, P. Chinowsky and J. E. Taylor, Spanning cultural and geographic barriers with knowledge pipelines in multinational communities of practice, *Journal of Construction Engineering Management*, **141**(4), pp. 04014091, 2015.
21. E. Holland, Mentoring communities of practice: what's in it for the mentor?, *International Journal of Mentoring and Coaching in Education*, **7**(2), pp. 110–126, 2018.
22. P. W. Irving, D. McPadden and M. D. Caballero, Communities of practice as a curriculum design theory in an introductory physics class for engineers, *Physical Review Physics Education Research*, **16**(2), p. 020143, 2020.
23. A. Mavri, A. Ioannou and F. Loizides, Cross-organisational communities of practice: Enhancing creativity and epistemic cognition in higher education, *The Internet and Higher Education*, **49**, p. 100792, 2021.
24. C. Egwuonwu, I. Miller, K. Jensen and J. Martin, Virtual communities of practice: Social capital's influence on faculty development, *2020 ASEE Annual Conference*, Virtual, 22–26 June 2020.
25. R. Streveler H. Matusovich, C. Carrico, S. Brunhaver, S. Sheppard, H. Chen, A. Harris, R. Abhyankar and M. Sama, Professional engineering pathways study: Using a community of practice model to propagate findings and engage the community, *2017 ASEE Annual Conference*, Columbus, Ohio, USA, 24–28 Jun 2017.
26. K. K. Janke, H. H. Seaba, L. S. Welage, S. A. Scott, S. M. Rabi, K. A. Kelley and H. L. Mason, Building a multi-institutional community of practice to foster assessment, *American Journal of Pharmaceutical Education*, **76**(4), pp. 1–7, 2012.
27. M. Borrego and L. K. Newswander, Characteristics of successful cross-disciplinary engineering education collaborations, *Journal of Engineering Education*, **97**(2), pp. 123–134, 2008.
28. A. Mostafavi, J. L. Huff, D. M. Abraham, W. C. Oakes and C. B. Zoltowski, Integrating service, learning, and professional practice: toward the vision for civil engineering in 2025, *Journal of Professional Issues in Engineering Education & Practice*, **142**(3), p. B4013001, 2016.
29. E. Coakes and S. Clarke, *Encyclopedia of Communities of Practice in Information and Knowledge Management*. IGI Global, Hershey, PA, USA, 2006.
30. R. K. Yin, *Case study research and application: Design and methods*, 6th ed. SAGE Publications, Thousand Oaks, CA, USA, 2018.
31. J. W. Creswell and J. D. Creswell, *Research design: Qualitative, quantitative, and mixed methods approaches*, 5th ed. Sage Publications, Los Angeles, CA, USA, 2018.
32. H. J. Rubin and I. S. Rubin, *Qualitative interviewing: The art of hearing data*, 3rd ed. Sage, London, UK, 2012.
33. S. C. Dwyer and J. L. Buckle, The Space Between: On Being an Insider-Outsider in Qualitative Research, *International Journal of Qualitative Methods*, **8**(1), pp. 54–63, 2009.
34. J. Saldaña, *The Coding Manual for Qualitative Researchers*, 4th edition. SAGE Publications Ltd, Thousand Oaks, CA, USA, 2021.
35. M. B. Miles, A. M. Huberman and J. Saldana, *Qualitative Data Analysis: A Methods Sourcebook*, 4th edition. SAGE Publications, Los Angeles, CA, USA, 2019.
36. Y. S. Lincoln and E. G. Guba, But is it rigorous? Trustworthiness and authenticity in naturalistic evaluation, *New Directions for Program Evaluation*, **1986**(30), pp. 73–84, 1986.
37. J. W. Vollet and T. A. Kindermann, Promoting persistence: Peer group influences on students' re-engagement following academic problems and setbacks, *International Journal of Behavioral Development*, **44**(4), pp. 354–364, 2020.
38. L. Zhao, Y. Lu, B. Wang, P. Y. K. Chau and L. Zhang, Cultivating the sense of belonging and motivating user participation in virtual communities: A social capital perspective, *International Journal of Information Management*, **32**(6), pp. 574–588, 2012.
39. K. George and R. L. George, Cooperative learning reflection: Virtual connections post-COVID, *Transformative Dialogues: Teaching and Learning Journal*, **15**(3), 2023.
40. D. W. Johnson and R. T. Johnson, Making cooperative learning work, *Theory into Practice*, **38**(2), pp. 67–73, 1999.
41. W. C. Lee, B. D. Lutz, H. M. Matusovich and S. Bhaduri, Student Perceptions of Learning about Diversity and its Place in Engineering Classrooms in the United States, *International Journal Engineering Education*, **37**(1), pp. 147–162, 2021

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