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From Disciplinary Roots to Interdisciplinary Identities: Biology Integration Institutes Promote Interdisciplinary Identity in Engineering Graduate Students

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Abstract

Interdisciplinary (ID) STEM research enables scholars to cross disciplinary boundaries and generate new knowledge (Mansilla, 2017; Frodeman et al., 2017). For STEM graduate students, participation in such research can shape both disciplinary and ID researcher identities, influencing professional trajectories, belonging, and ability to navigate complex scientific landscapes (Leshner & Scherer, 2018; Simpson & Bouhafa, 2020; Singer et al., 2020). However, developing an ID identity presents challenges as students balance conflicting expectations across sociocultural contexts. For example, training in graduate programs and research labs may conflict with perceived outcomes in interdisciplinary centers.

Biology Integration Institutes (BIIs) provide innovative spaces for graduate students to engage in ID training and collaboration, serving as incubators for scientific breakthroughs (NSF, 2022) and shaping identity development. Grounded in Figured Worlds theory (Holland et al., 1998), Science Identity theory (Carlone & Johnson, 2007), and Identity-Trajectory theory (McAlpine, 2012), this study examines how engineering graduate students position themselves as ID researchers in a BII. Using a multiple case study approach (Merriam & Tisdell, 2015), we conducted semi-structured interviews with seven students from different institutions, labs, and personal backgrounds. This paper focuses on engineering students affiliated with the same BII. Data were analyzed through thematic coding and constructivist grounded theory (Charmaz, 2006).

Through our analyses, we explored how students define and contrast Figured Worlds—universities, labs, the BII, and relationships with peers and faculty—and how engineering backgrounds shape ID identity development. Further, we revealed how students reconcile or resist tensions between disciplinary, institutional, and interdisciplinary contexts. Findings suggest engineering training primes students for interdisciplinary thinking, and BIIs provide the infrastructure to apply these skills, produce tangible outcomes, and develop as ID researchers. Labs and BIIs emerged as the most influential spaces for identity formation, with their proximity and alignment in skills, relationships, and opportunities easing transitions across contexts. Simultaneously, personal and academic Figured Worlds sometimes conflicted, complicating integration of ID researcher identity with other aspects of self. Variation in how students defined and valued ID work further shaped whether they recognized themselves as interdisciplinary scholars.

This research illustrates the potential of BIIs as innovative graduate training models that foster diverse, inclusive, and supportive communities. By surfacing both drivers and barriers to ID identity formation, findings inform assessment, evaluation, and continuous improvement of graduate programs. In order to prepare the next generation of interdisciplinary scientists, it is essential to understand how students navigate disciplinary and contextual boundaries as well as the longevity of the effects of ID research participation.

Introduction and Literature Review

Need for Interdisciplinary Scientists

Interdisciplinary (ID) research in STEM (science, technology, engineering, and mathematics) has taken center stage in driving reform in research, education, and career development. This multi-dimensional approach to STEM strategically fuses diverse methodologies and expertise to blur the boundaries that have traditionally divided individual disciplines, resulting in a space where researchers create, negotiate, and communicate new knowledge and alternative solutions to phenomena of interest [1], [2]. Undergraduate and graduate students participating in ID research learn about the theory and process of ID research, produce rigorous research, and prepare to solve today's "wicked problems" no one discipline can adequately address [3], [4], [5]. Leading scientific organizations recognize the significance and need for such transformative work. For example, the National Research Council's (NRC) Bio2010 report calls for more ID undergraduate education to better prepare future biomedical researchers [6]. The Vision and Change Report advocates for an increase ID research opportunities in undergraduate introductory STEM courses [7]. Additional reform movements advanced by federal funding agencies actively support ID projects (e.g., Biology Integration Institutes (BIIs) [8], Global Convergence Research [9], and Roadmap initiative [10]). While federal agencies, national organizations, and industry advocate for ID research, there remains a gap in the understanding of what it takes for graduate students learning to conduct ID research to identify as ID researchers.

Processes of and Influences on Identity Formation

The process of identity construction is heavily context-dependent, not only involving external environments but also personal experiences. Graduate students and early career scientists who engage in STEM research can attain a science or STEM identity, which enables them to take charge of their learning, achieve their career and professional goals, and gain a sense of belonging as a scientist in their field of study [11], [12], [13], [14], [15]. Moreover, graduate students who participate in ID research attain an ID researcher identity and consequently face the challenge of breaking disciplinary boundaries [16]. According to Holland et al. (1998), identity "is a concept that figuratively combines the intimate or personal world with the collective space of cultural forms and social relations" [17]. In other words, identities are practiced 'selves', dynamically molded by intrinsic motivators and extrinsic socio-cultural norms. Identities are under constant development as individuals progress through their lives and encounter shifts in their personal motivations and their environments.

There has been a noticeable gap in research concerning the diverse interplay of scientists' identity dimensions across various academic and personal contexts. Current literature regarding identity development of graduate students and developing scientists tends to focus on the effects of one context on one aspect of individuals' identities. Graduate student STEM researchers must simultaneously balance relationships with advisors, mentors, and peers [18], [19]; demonstrate competence in scientific spaces [20], [21], [22]; navigate the unique cultures and expectations of their university, department, and laboratory [19], [23], [24], [25]; and manage personal and familial obligations [25], [26], [27]. Furthermore, the formation of a STEM identity can be at odds with the prevailing norms and culture within academic spaces, especially for marginalized groups in STEM fields [28], [29], [30], [31], [32], [33], [34].

This delicate balancing act is compounded by disciplinary siloing across STEM fields, which divides researchers from each other, impedes ID research outcomes, and disrupts the formation of an ID identity [35]. Deep-rooted disciplinary training often prevents the acceptance of perspectives from other disciplines [36], which leads to attitudinal resistance. Challenges also include using jargon while communicating across disciplines [36], [37] and during interactions at disciplinary boundaries [37]. Additionally, the lack of consensus in defining ID research and ID in general [38], [39], [40], [41] affects the structuring of ID activities, evaluation strategies, researcher identity formation [42]. Furthermore, the current academic climate places high value on scientists' mastery of specialized disciplinary skills to secure funding, making it challenging for individuals to pursue career paths beyond their primary discipline [36]. Researchers are skeptical about the longevity of ID collaborations because they must dedicate a substantial amount of time to cultivating collaborative relationships, establishing a shared vocabulary, and refining a unified perspective incorporating diverse viewpoints [43], [44]. At the institutional level, the scarce understanding of what processes, modes, and outcomes support and facilitate ID collaboration poses a challenge for executing and organizing ID research [44], [45].

Fostering ID STEM Identity Development in Research Centers

Despite the challenges involved in conducting ID STEM research and training, there exist research centers which promote ID work by providing a physical space and infrastructural support for stakeholders with varied expertise to collaborate and integrate across disciplines and build social relationships [44], [46], [47]. For example, The National Science Foundation has funded numerous ID research endeavors in the field of biology [7], [48], including an initiative to build and fund Biology Integration Institutes (BII) [8]. Through cross-departmental and institutional partnerships, BII researchers advance biotechnology to translate discoveries about life's innovations into solutions for complex societal challenges [8]. BIIs and similar centers create a dynamic space where people can easily traverse disciplinary boundaries [47], [49] to promote learning, synergy, creativity, and research productivity [50]. An ID community of practice [51] allows members to form a sense of belonging, develop identity, and engage in collective learning processes to share ideas and resources [52].

Fostering ID STEM Identity Development in Engineering

The development of interdisciplinary (ID) identity is a critical component of graduate engineering education, shaped by supportive teaching systems, institutional incentives, and students' lived experiences. Research highlights the importance of ID teaching systems in promoting students' ID competence and scholar identity development [53]. Student-centered instruction, cohesive curricula, aligned incentive structures, and dedicated spaces for interdisciplinary engagement support students in integrating knowledge and synthesizing diverse perspectives [53], [54]. At the same time, misalignment between institutional definitions of ID graduate education and students' expectations, along with broader structural barriers to incentivizing ID research, teaching, and service, underscores the need for systemic change [55], [54]. Longitudinal work using the Future Possible Selves (FPS) framework further illustrates how engineering graduate students' self-perceptions and aspirations evolve as they navigate ID pathways [56]. Collectively, this research demonstrates that fostering interdisciplinary STEM identity in engineering requires coordinated attention to pedagogy, institutional structures, and student development.

Study Goals and Research Questions
Each of the contexts, relationships, and responsibilities managed by STEM graduate students has a unique set of socio-cultural expectations that influence the development of graduate students' personal and professional identities. Unification of these contexts may result in conflicting conceptions of progress, belonging, and accomplishment that make it difficult for graduate student researchers to evaluate their level of success at attaining the identities they desire, especially that of an ID researcher. Misalignment of expectations among identity dimensions hinders the development of an ID identity [17], which deprives the academic community of valuable research contributions that will not be realized.

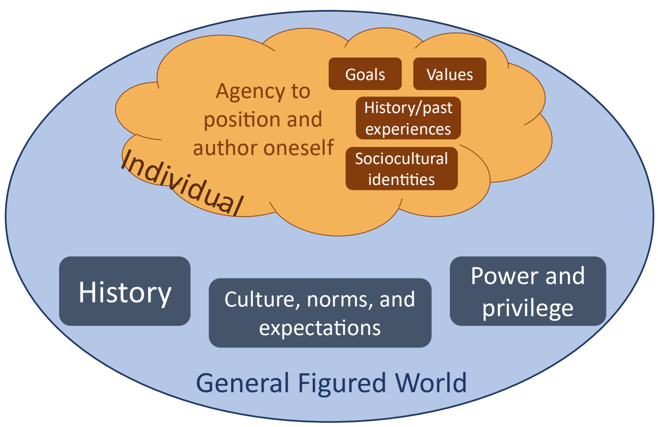
In order to address these challenges and limitations, <u>this study examines how engineering graduate students identify and position themselves as ID researchers while traversing multiple academic and personal sociocultural contexts, including a BII</u>. This is done by applying constructs from the theory of Figured Worlds [17], Science Identity Theory [57], and Identity-Trajectory Theory [58], [59]. Using a multiple comparative case study approach [60], the authors coded semi-structured interviews with seven students from different institutions, labs, and personal backgrounds. This paper focuses on two of those students, who cite their engineering experience and who are affiliated with the same ID BII.

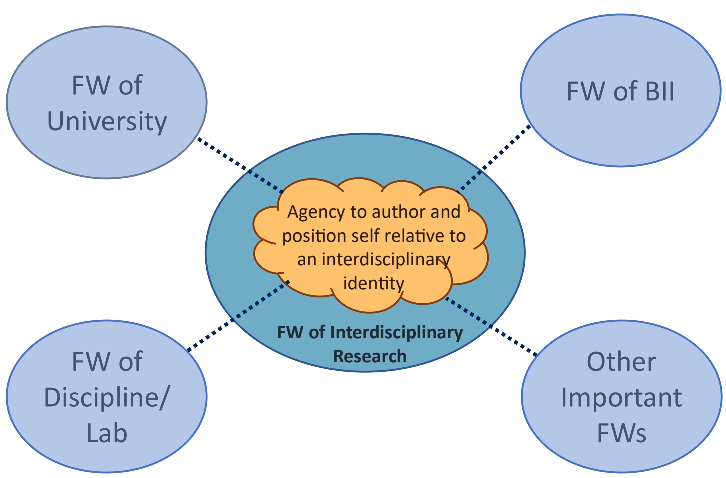
Here we answer the following question: How do two engineering graduate students in an ID BII define and contrast different figured worlds they inhabit (university, discipline, lab, BII) and their influence on the development of an ID researcher identity? Investigations that fall under this umbrella question include identifying, characterizing, and analyzing alignment and strength of the students' FWs. Additionally, we investigate if and how the students recognize themselves as ID researchers and how their engineering experience specifically influences this identity.

Theoretical Frameworks
Figured Worlds
BIIs, research labs, academic disciplines, and universities function as figured worlds (FWs), as described by Holland et al. (1998) [17], in which individuals position and author themselves in and across socio-cultural contexts, including formation and reformation of oneself. FWs are the settings in which socio-cultural "subjectivities" (i.e. expectations and norms) are enacted and reproduced. FWs are "historically contingent, socially enacted, [and] culturally constructed" [17], demonstrating the importance of the temporal as well as the socio-cultural factors on the individuals' development. FWs can be recognized fields or abstract realms of social life, for example the FWs of Harvard University, biology, civil engineering, or whiteness. Each FW includes its own history, culture, expectations for its members, and patterns of power and privilege enacted by the members (**Figure 1**). The individual entering the FW brings with them their own history and past experiences, goals, values, and sociocultural identities. Throughout their experiences in the FW, the individual has the agency to position and author themselves in relation to this FW and others (**Figure 2**). In this theory, individuals hold multiple identities that are iteratively shaped by sociocultural practices of the FWs they occupy, and the degree of agency they hold to organize their experiences and develop their own self-understandings. Inhabiting multiple FWs can result in the cultivation of seemingly incompatible identities (e.g., trainee and leader), owing to tension between cultural logic earned early in life and subject position imposed upon individuals by significant socio-cultural structures [17]. Identities within

FWs are established when the FW is interpreted as valid, true, fair, and relevant to the individual, and if the identities are seen as desirable and possible to attain [17]. The general process of identity development in a FW involves exposure to individuals who identify with the FW, evaluation of the socio-cultural norms in the FW, and alignment of the events and experiences of one's own life to the FW [17].

The Figured Worlds framework is used in STEM education to examine how learning environments shape identity. Research shows that alignment across contexts supports transfer students' development [61], that medical and clinical trainees navigate power dynamics as they form professional identities [62], [64], and that Latina computer science undergraduates actively redefine disciplinary norms within computing [63]. In engineering education, studies reveal a disconnect between academic problem-solving and industry discourses among senior students [65], suggesting limited integration between school and professional worlds. However, design-based work demonstrates that even a single, complex studio task can shift participation toward authentic disciplinary practices and foster more equitable team interactions [66]. Together, this scholarship underscores the value of the FW framework for understanding and intentionally shaping identity development in engineering and broader STEM contexts.





Figures 1 and 2: (1) Example of a generic FW (blue oval) and its components when an individual (orange cloud) enters into it. (2) Hypothesized relevant FWs that influence a graduate student's ID identity as they navigate their involvement in their BII and other contexts.

ID BIIs function as FWs that wield substantial influence in shaping graduate students' identities and sense of belonging through the cultural norms and expectations they establish. BIIs serve as incubators for the next generation of scientific breakthroughs, frequently led by graduate student researchers [8] and as such, ID STEM identity development is directly influenced by experiences and engagement in these institutes.

Science Identity

There are specific identity dimensions that influence the development of a science or STEM identity for graduate students in multiple FWs. Carlone and Johnson (2007) developed a model of Science Identity through their research on the experiences of women of color over the course of their undergraduate and graduate studies in science and into science-related careers [57]. They assert that being and enacting an identity – which here means the type of person one is, is seeking to be, and is representing – requires that "one makes visible to (*performs for*) others one's *competence* in relevant practices, and, in response, others *recognize* one's performance as credible" [57]. The process of recognition is closely tied to the concept of agency beliefs, which are essential for individuals to take control of their own identities and career choices. Godwin et al. (2016) suggest that students' agency beliefs are significant predictors of engineering career choice, alongside other factors such as math and physics identities [67]. Furthermore, Carlone and Johnson's model makes explicit that one's gender, racial, and ethnic identities also affect one's science identity, emphasizing the role of socio-cultural structures in shaping what it means to be a particular "type" of person. These systemic and structural influences are important for understanding the ways university and career-related settings reproduce social norms for those who attain science identities. This framework shows that individuals hold multiple identities that intersect (i.e., personal identities with STEM/science identity), and that, often, positive STEM identity trajectories are typically undermined by institutional, structural, and hierarchical influences [57].

Identity-Trajectory

McAlpine and Amundsen (2011) developed a theory of Identity-Trajectory of early career academics and doctoral students that "emphasizes the integration of past-present-future in the experience of academic work, and the individual's desire to enact intentions and hopes over time" [59]. This framework situates the academic work in personal and past experiences of the student and tracks the student's movement in their program and life through time. The theory outlines three interconnected "strands" that develop over time as students advance in their programs [58]: (1) Networking: present and past relationships which serve as resources as well as carry responsibilities; (2) Intellectual: written and oral contributions to the field leading to recognition; and (3) Institutional: organizational responsibilities and resources. The networking, intellectual, and institutional strands that emerge during doctoral work are crucial for recognition by significant scientific others, influencing both progress and limitations in identity development [59]. By centering the individual's perceived agency, this structure provides a nuanced understanding of how day-to-day experiences shape graduate students' learning, self-evaluation, and achievement of desired goals and identities.

The combination of Figured Worlds, Science Identity, and Identity-Trajectory theories (demonstrated in **Figure 3**) offers a nuanced framework for investigating engineering graduate students' ID STEM identity development as they traverse various FWs in pursuit of their goals.

Doing so allows us to explore the intersections of several academic and non-academic FWs, each with their own unique set of norms and expectations that meld with the influence of institutional and systemic cultures, students' pasts, and students' personal life experiences that shape the attainment of an ID STEM identity.

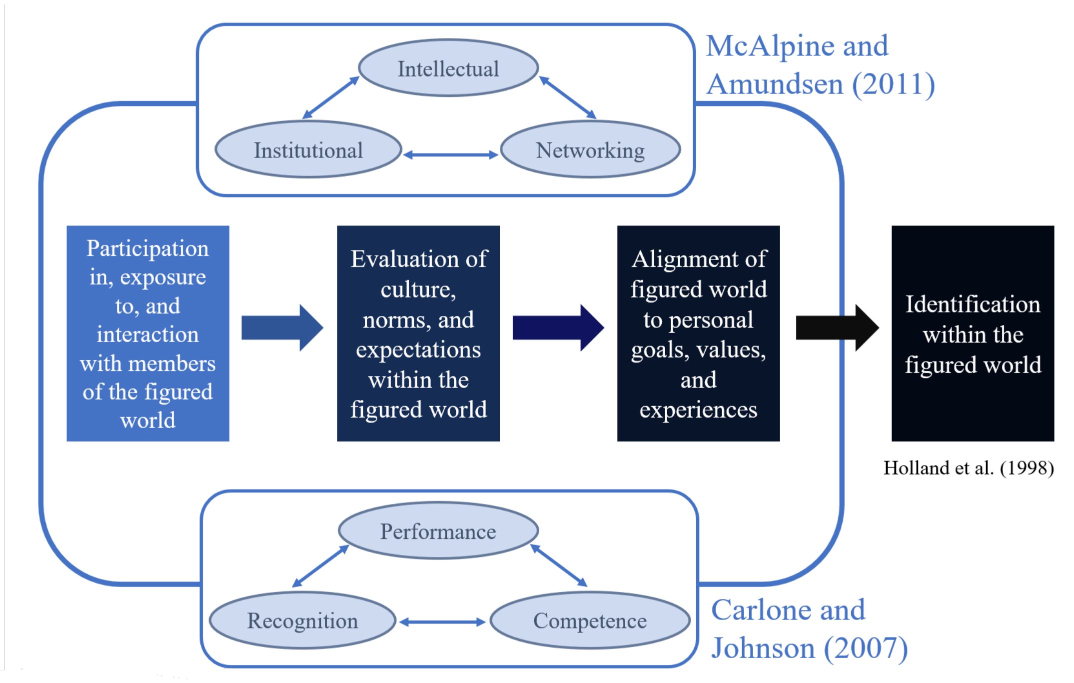


Figure 3: Combination of theories and constructs in development of a science identity in a sociocultural context.

Methods

This work is part of a larger longitudinal study investigating the development of ID STEM identity of graduate students active in BIIs. It is characterized as a multiple or comparative case study, in which data is collected and analyzed from several cases [60], [70], [71], using the constructivist grounded theory (CGT) approach [68], [69]. Investigators centered their participants throughout the research process, and interviews focused on the lived experiences of engineering graduate students in a BII as they traversed various FWs and developed an ID STEM identity. Each individual graduate student member of a BII acts as a case. Here we highlight two engineering students in the same BII, drawing connections across cases. We acknowledge that this study focuses on two students and does not support broad generalization. However, comparative case study methodology enables an in-depth examination of the data collected from these participants. The selected cases' experiences and perspectives are particularly relevant to ongoing conversations within engineering education. Grounded in established traditions of educational case study research, this approach allows us to provide a rich, contextualized account of their experiences and insights. Ethical conduct of research was secured in this work through the IRB review process to protect participants' privacy and confidentiality during data collection and analysis (IRB-2023-1332).

Participants

Participants were recruited via email listservs for BII member mailing lists and brief announcements during BII group meetings. Seven graduate students consented to participate in the study, two of whom describe engineering experience and are focused on in this paper. These two students are affiliated with the same BII, joined in the same semester, entered their graduate programs in the same academic session, and are both pursuing a PhD, but they attend different universities, conduct research in different departments and labs, and differ in demographic categories. **Table 1** below summarizes the two students' characteristics.

Characteristic Category	Student A	Student B
BII Membership Start Date	Fall 2021	Fall 2021
University Affiliation	Institution 1	Institution 2
Desired Degree Type	PhD	PhD
Program Start Date	Fall 2021	Fall 2021
Discipline	Developmental Biology, Bioengineering	Quantitative and Systems Biology
Department	Chemical and Biological Engineering	Biomedical Engineering
Gender Identity	Man	Woman
Racial and Ethnic Identity	White	White
English as a First Language	Yes	Yes
Sexual Identity	Heterosexual	Bisexual
Disability Status	None	A mental health disorder, A temporary impairment due to illness or injury
First in Family to Pursue Graduate Education	No	No

Table 1. Summary of demographic factors and relevant academic affiliations of engineering graduate student cases.

BII Context

Both engineering students engaged in the same BII. Researchers in this BII investigate the ways living systems coordinate and integrate stimuli that influence cellular structure and function. They use quantitative measurements and simulations to integrate signals across different scales of biological systems. The institute fosters cross-university collaboration by partnering with six universities. It contains four research subdivisions ("thrusts") bridged by a common core division that provides quantitative, computational, and technical support to all other subdivisions. Trainees and PIs coordinate collaboratively across thrusts to advance projects in the BII. They share tools, such as reagents and imaging techniques, to promote consistency across the different projects. Additionally, the BII developed a common data integration and simulation platform to ensure that results are integrated in a rigorous and systematic manner. As a result, this BII brings together researchers and engineers across diverse fields and institutions, and members break through traditional disciplinary silos to make transformative biological research advancements.

Data Collection

In this study, we used a semi-structured interview protocol to enable adaptive questioning and tailored follow-up with each participant [73]. Open-ended questions allowed the participants to respond to elements that were most salient to them. The interviewer asked questions about FWs which influence how participants see themselves as ID researchers within academic (university, department, discipline, lab, and BII) and personal contexts (e.g., peers, family, home communities, race and ethnicity, faith, etc.). Participants' descriptions allowed the researchers to analyze how the FWs are aligned or misaligned, the degree of ease while traversing from one context to another, and the consequential development of ID STEM identities. The protocol was piloted with colleagues from our research group who were unaffiliated with the BII. Iterative changes were made before finalizing and employing the interview protocol.

Data Analysis

Interviews were transcribed verbatim, and data analysis was conducted through their examination. Interview transcripts were coded and analyzed primarily through inductive thematic analysis. Thematic analysis involves a) initial reading, reflection, and insight from interview transcripts, b) code organization, comparison, and labeling, c) re-evaluation and verification of the codes, and finally d) narrative development [74]. The major tenets of thematic coding are aligned with data analysis using CGT, an iterative process among data, conceptualization, and theorization. Analysis began with initial coding, in which the investigator separated data into categories while remaining open to exploring all emergent possibilities. Initial coding was followed by focused coding, to synthesize and explain larger segments of data.

Transcripts were coded by sections devoted to each FW, and participants' descriptions of and experiences within each of their FWs were examined holistically. Connections were then made across FWs and across participants, noting alignment as well as tension or conflict. Once the initial round of coding was completed (by author E. G.), a second coder (author G. C.) independently reviewed each transcript to ensure consistency. Any discrepancies in coding were resolved through discussion and iterative codebook refinement until a minimum of 80% agreement was reached between the coders [75]. Emphasis was placed on key events, critical incidents, and significant experiences that shaped the participants' identities relative to ID STEM research as they navigated their FWs.

Results and Discussion

Characteristics and Influence of FWs

<u>Motivations</u>

Choosing to pursue a graduate degree in any discipline is not a simple decision. The engineering students in this study had similar motivations for pursuing PhDs in their fields in their universities, including the fact that the degree is required for their greater career goals. They also both cited their previous academic or work experience that spurred interest as influencing their decisions. Student A uniquely described the perceived logic, ease, or accessibility of graduate school at the time of his decision, as well as an overall interest in expanding his research knowledge and experience. Student B mentioned discussions with peers and graduate students as influential in her decision.

<u>Meaning and Significance of ID</u>

Ideas about what ID means and why it is important ground the process of identity development as an ID STEM researcher. Student A described ID as involving multiple disciplinary perspectives that are required to address and understand complex problems and to more wholly understand a common phenomenon of interest. Student B mentioned that ID work expands knowledge on other disciplinary information, skills, norms, and processes. She furthered this idea by saying that ID fills a noticeable gap where disciplines can cross over and minimize siloing, both by an ID individual themselves acquiring expertise from multiple disciplines, perspectives, or approaches, as well as by disciplinary experts "talking" to each other in order to fill gaps. Interestingly, in his response, Student A also explained that drawing the lines between disciplines determines what is considered ID. He said that ID can involve different perspectives or specialties even within the same umbrella discipline.

FW of the University

Both students described having overall positive views and experiences in their universities. Emphasizing the institutional strand, Student B cited her university's reputation and legacy leading to more opportunities and Student A reported his university's student support mechanisms both academically and otherwise. It is notable that during this portion of the interview about the FW of the university, both students also reported some details about their experiences in their labs and BII. This demonstrates the inherent alignment of these FWs for these students, or perhaps the relatively weaker influence of the FW of the university compared to the lab and BII.

While conveying their experiences in their university, several common themes related to expectations of them as graduate students and metrics of success emerged related to performance, competence, and recognition, especially self-recognition as successful. Both Student A and B mentioned their employment contract, working hours, required coursework and GPA, or TA requirement, the need for research advancement and continuous progress, and production of publications as important to their success as graduate students in their universities. In addition to these structural and institutionally-driven expectations, both also acknowledged the importance of their own self-recognition of the work, effort, and holistic growth and progress they make throughout their degree programs. When asked about their view of themselves in their universities, only Student A definitively stated seeing himself as a successful graduate student thus far, based on his perception of himself as being comparable to peers and other graduate students and his ability to apply and build on knowledge gained earlier in his academic career. Student B faced challenges related to stress and other mental health concerns, experienced limited access to her PI and other mentors, and experienced shifts in the typical grad student timeline when she changed departments, all leading to her perception of herself as "doing okay," rather than unambiguously successful.

That said, both students described aspects of their university experiences that impact their ID STEM identities. Student A depicted his university as providing opportunities to collaborate with others from different disciplines, and Student B commented that her university offers opportunities to bridge disciplines as an individual by gaining disciplinary knowledge and skills herself. These descriptions depict the FW of the university as offering institutional, intellectual, and networking-related supports for these graduate students. Still, only Student A recognized himself as an ID researcher specifically because of the influence of his university.

FW of the Lab

Like in the FW of the university, common themes emerged in the FW of the lab related to expectations and metrics of success of the students. In line with the constructs of performance, competence, and the intellectual strand, both Student A and Student B highlighted engagement, critique, and discussion in lab meetings and about each other's work, research advancement, technical skill building and presentation skill building as important for their success in their labs. In addition, Student A referenced important aspects including project and time management, spending lots of time in the lab, production of tangible research outputs and dissemination at lab meetings and conferences, and acquisition of high-quality results efficiently. Like in the FW of the university, he underscored the importance of self-recognition of work, effort, and holistic growth as he progresses through his research. Based on these characteristics, both students recognized themselves as successful graduate students in their respective labs.

Peers and others in the lab environment also play a large role in the students’ experiences that impact their identity development, highlighting the role of the networking strand in this FW’s influence. Student A placed emphasis on the relationship he has with his PI. He described the relationship as overall supportive, especially his PI’s practice of recognition and mentorship of the whole person, rather than just the researcher. He described having an apprenticeship relationship, with his PI as a leader and mentor and the intellectual and resource expert. As previously stated, Student B had limited access to her PI because of his high-level administrative responsibilities, so she had a senior member of the lab as a mentor and supervisor who can offer support, guidance, and gauge her progress in her work. Both students talked about relationships with their other lab mates as important in their lab experiences. They both described that they are able to build a mutually-supportive community with their core group of lab mates. Additionally, Student B extended her peer network with academic activities outside of lab and engaged with peers outside of lab in the same research area, bolstering her sense of belonging.

Student A and B both indicated challenges that make progress or success difficult in the lab. They both experienced feelings of not doing enough, not seeing the impact or output of their work, or pressure to do so much work in a short time, suggesting a lack of recognition of themselves as successful researchers. This is compounded by Student B’s limited access to support and assurance from her PI, as well as Student A’s experience of mismatched expectations with his PI about metrics of success and research progress, leading to lack of recognition.

Despite the challenges, Student A and Student B definitively called themselves ID researchers because of their lab experiences, evidenced by exposure, collaboration, and discussion with others across topics and disciplines. Student A noted that his research discipline (developmental biology, bioengineering) by nature integrates across knowledge and expertise. Similarly, Student B explained that she herself has acquired ID knowledge and experience by conducting work in multiple disciplines (computation, biology). The repeated day-to-day exposure, collaboration, and engagement in research that graduate student researchers have in their lab may explain the relatively stronger and more definitive comments that Students A and B make about this FW’s influence on their ID STEM identities compared to the FW of the university.

<u>FW of the BII</u>

Student A and Student B joined the same BII at the same time and have continuously been involved up through the publication of this work. Descriptions of the BII align with support in the institutional and networking strands, as well as achievement in performance. Both students expressed appreciation for the integration, exposure, and access to others with similar goals and different disciplines in a concentrated effort that they experience in this BII. Furthermore, both described being able to translate and transfer their knowledge, experience, and expertise between the BII and their labs. Student B notably shared that membership and engagement in the BII makes available opportunities that she otherwise would not have had, including funding, research experiences, and network expansion. Already this sets the FW of the BII as a significant context through which ID STEM identity development is influenced.

Whereas Student B perceived no defined expectations and metrics of success for graduate students in the BII, Student A described several: production of tangible outputs for institute-specific activities and the broader academic community, attendance and engagement in institute activities, and collaboration with BII members.

There are numerous ways institute members interact and consequently impact the development of each other's research and sociocultural identities. Student A and B described the impact of interactions with other members of the BII, highlighting the networking strand as well as recognition as ID. Both mentioned networking and community-building with researchers across career stages and notoriety in a welcoming environment, the practical application of other techniques/approaches/methods to their own projects and vice versa, as well as increased engagement and interaction increasing their comfortability, confidence, sense of belonging in the BII. They both mentioned that they use others' work as a basis for comparison, and Student B furthered this by saying that she is able to see the practical side of the scientific process through interactions with BII members, rather than only the completed, refined outputs like publications and finalized presentations. Still, Student B recognized that there is still some siloing and separation among the sub-groups in the BII, and this is substantiated by Student A's observation that some people or branches of the BII are more relevant to his own work than others. Besides this siloing, the only other challenge that makes success and progress difficult in the BII was scheduling and time management difficulties, brought up by both students.

Both Student A and Student B's identities are deeply affected by their experiences in their BII, underscoring the importance of infrastructure provided by the BII to support ID research and professional development (institutional strand). Both students recognized and called themselves ID STEM researchers specifically because of the BII, and they both expressed personal enjoyment about doing ID work. Student B saw herself developing ID research competencies through her experiences in the BII, and Student A shared that he was able to apply his long-held ID mindset and training in a concentrated effort through the BII. He noted that the BII is ID because members are not just sharing and sourcing other expertise but producing transformative and creative advancements.

Other FWs

In addition to the FWs described, Student B was also impacted by her teaching identity. Several family members, including her parents, are teachers and have influenced her own ideas about herself as an instructor. She had yet to take on the Teaching Assistant role but stated that it was a program requirement and was excited to step into that role.

Alignment and Tension

Overall, the FWs of the university, lab, and BII all share common themes related to expectations and metrics of success for the two engineering graduate students. All three FWs emphasized the importance of collaboration, networking, and exposure to others across disciplines in the development of an ID identity. The students' experiences in the lab and BII had a significant impact on their development of ID identities, framed by their own motivations and conceptions of what it means to be ID. There seemed to be tension between the structure and institutional expectations of the university and the more flexible, adaptive environment of the lab and BII. Additionally, the students' experiences in the lab and BII had stronger influences on their ID identities than the university, suggesting that the former provide more supportive and collaborative contexts for their research development or more opportunities to do so. While the students recognized the importance of their university experiences, they also acknowledged challenges such as limited access to support and assurance from their supervisors, which can impact their progress or success. Additionally, at the end of the interviews, both Student A and Student B explained the difficulty but importance of work-life balance. Both of them acknowledged that at the time of the interviews and degree progression, academic work took precedence, and time management was a critical skill to harness. However, they still both recognized the importance of self-care. Overall, the alignment and tension among the FWs highlight the complex interplay of different contexts in shaping the students' identities as ID STEM researchers.

Specific Influence of Engineering

Intertwined with these FWs' characteristics, both students' engineering disciplinary backgrounds influence their development as ID STEM researchers. Here we provide quotations from the interviews when students described how their backgrounds and engineering training affected them as they navigated their universities, labs, BII, and other FWs.

<u>Student A</u>

Student A conducts developmental biology research while in the bioengineering graduate program at his university, which integrates biological sciences, chemistry, biomolecular engineering, chemical engineering, and computer science and engineering. When asked about his experience at his university, he explained:

> "Within my program, I'm in a different department than my program is under…like a lot of my peers are in my home department under their program, and our programs are slightly different. So it's, it seems like with my program, there's a lot more emphasis on like the traditional route of like gaining knowledge and less on…productivity in the sense of like publishing things…The exams are more structured around, like, what you know, what you've learned, what skills you have built. Whereas like some of the other programs I've, I've seen are, are designed are more like, very cut, clean steps like you've done *this* so far. So you're moving on to the next stage, and then by that stage we want *this* done and stuff like that. Whereas I feel like mine is much more open ended, like it's, it's more of, like tailored to who you are as a student. And because of that, it can be bent to fit you the best."

From this description, we see that there is some separation from others in Student A's bioengineering program because he is housed under a different departmental designation than is typical of someone doing similar research. He saw this especially in comparison to his peers. Within his degree program, expectations and marks of success were based on application of knowledge and experiential learning, rather than the typical outputs like "publishing things." Even though there aren't clear cut and defined checkpoints of progress, he could still progress based on his goals and ideas. This flexibility of his program (institutional strand) allowed for more agency in the learning and development process, further evidenced by the comment later in the interview that while "at times you might be feeling…like you're behind. But you're still, as long as you're being, I guess, productive in the sense that you're still trying, you can still show that, which is nice." Though he could not easily compare himself to others in the same program, he authored and recognized himself in his position by seeing that success could be marked by putting in effort into the work in addition to meeting the program's conceptions of success and progress (performance and competence). Thus, the FW of bioengineering for Student A is distinct from but related to the FWs of his peers in biology and related STEM programs. For Student A, bioengineering is marked by application of knowledge, experiential learning, skill-building, and self-motivation, and mastery through self-pacing.

These comments feed into the ways Student A experienced his lab. He described the differences in his biology work compared to other engineering students, citing his strong experimentation and research design skills, particularly efficiency in running concurrent experiments (competence):

> "Just being in a biology based lab, it feels like more work than a lot of other labs because I'm in the chemical engineering department. So it's fun to talk to others because it's a totally different time frame with stuff. So you have to have the patience of dealing with biology in a sense. You have to wait for stuff to grow...I feel like I've built a really strong, robust like techniques to like make sure my experiments are fully like, have all the controls set up and stuff like that. Because if you make a mistake, you have to start over. But starting over could be like a week worth of waiting for stuff to happen…I've definitely… gotten good at performing larger experiments, because then you can do everything in parallel...If it takes a month to do it, at least you can do a dozen, dozen things at a time."

Student A straddles the disciplinary FWs of biology and engineering simply by conducting his research, and thus by being a bioengineering student. Based on his response, such boundary-spanning is outside of the norm for graduate students in the engineering departments at his university, resulting for him in what feels like more work. In doing so, Student A built strong competence in experimentation and research design and recognized himself as progressing and improving as an ID researcher in the lab.

When asked if he sees himself as an ID researcher given that he is a member of his BII, he responded:

> "Yes I do. Definitely. Because I'm part of [the BII], just because there's different facets of [the BII] with all the thrusts, but also just within my lab. I'm doing a lot of biology, but I'm also trained as an engineer, so I feel like that's just interdisciplinary in itself. Yeah."

It is clear that being a member of this BII contributes to Student A's sense of self as ID researcher, in tandem with the experiences and training from other contexts, especially his lab. Simultaneous membership in and overlap of both the FW of the BII and the FW of Student A's lab, which integrates biology and engineering, directly influence his recognition of himself as ID researcher. He further described the BII:

> "It's kind of cool to see how everything's broken out through the thrusts and see where you fit in. But also like, I definitely think I can't remember which thrust I'm in. And because it's nice to know that, you know, you can overlap between thrusts. So like, I know some of my projects fit in this thrust and so my projects may fit in a slightly different thrust. And so inter, interdisciplinary just within your projects within let alone like, within, between people as well."

For Student A, the FW of the BII has further subdivisions inside of it, and ID involves integrating them. "Forgetting" which thrust he is in suggests that the divisions are blurred in the ID work he does as a member of this BII. This is similar to the boundary spanning in his own graduate program outside of the BII. In the BII, Student A contributed to multiple thrusts by virtue of the nature of his developmental biology project. His ID researcher identity stemmed from the ability to do ID work in various FWs, but also because there is overlap among FWs that are all committed to ID advancements. While separate FWs, it is easy for Student A to traverse across them and use the knowledge and experiences from one FW in another. The application of ID knowledge and skillsets is pronounced in the FW of the BII, but also cultivated in own lab/discipline and past experience:

> *Interviewer*: Is that similar in your kind of training as a chemical or as an engineer as well, where you can sort of fit into these different, I mean it sounds like even from the fact that you're in a biology lab in a different, you know, sort of area. That similar kind of idea where you can kind of put your ideas in different, you know, puzzle pieces.
>
> *Student A*: Exactly. Yeah…I think the biggest thing that makes it feel interdisciplinary too, is also working with people that don't, I don't feel like are really similar in the field. Like I guess for me, like combining experimental with computational. Like, I don't I don't do computational, but we work with computationalists. So that feels interdisciplinary because then it definitely feels like, you do your thing there, they do their thing, but then you create something together. Instead of just sharing information you're also creating something as well. So I feel like that's the biggest, the biggest area where I feel interdisciplinary.

According to Student A, ID, especially ID in the BII, means collaborating with researchers from different disciplines. Furthermore, what makes such collaboration truly ID is that researchers are not just collaborating for the sake of collaborating, but are producing something transformative as a result. Student A's experience in the BII embodies his views on ID, in which individuals with different areas of expertise work together to build a more complete picture of a complex phenomenon of interest, or "put the puzzle together." These experiences have shaped his ID identity and informed his understanding of the value of collaboration across different fields. The boundary spanning behaviors, knowledge, and experience from Student A's experience in the bioengineering program and in his lab are furthered and mirrored in the FW of his BII, and doing so contributes to his recognition of self as attaining an ID STEM identity.

<u>Student B</u>

Whereas Student A bluntly cited his own engineering program and training as a definitive influence on his ID STEM identity that directly connected to his experiences in the BII, Student B's descriptions of the influence of her engineering background on her ID STEM identity, while similar, are more subtle. Student B conducts computational and experimental biology research in the biomedical engineering program at her university, initially accepted into the agricultural and biological engineering program.

Student B's research experience in her undergraduate engineering program forms the basis for her motivations to pursue graduate education and frames her view on the significance and meaning of ID. She described:

> "So I did my undergrad in agricultural and biological engineering. I ended up doing some research with algae and then helping out in the lab researching nematodes. And I liked that direction of doing research. I wanted to keep doing research... And I kind of wanted to stay in the research field, and I really like being in an interdisciplinary space."

In her undergraduate program, Student B bridged agriculture, biology, and engineering disciplines. She found interest and enjoyment in the research and saw her potential future in it, especially highlighting ID research. She saw graduate school and the PhD (the FW of the university) as a pathway to conduct research at a high level of ID expertise, management, and agency.

Regarding the FW of her lab, which integrates engineering, computation, and biology, Student B found herself at the intersection of disciplines that she feels are not enough in conversation with each other:

> "I really like this lab because I have an opportunity to do some computational work and some experimental work…I feel like there aren't enough people in the middle. And I always…see all these cool experiments happening and this cool, computational work happening, but it seems like there's some kind of divide. There's not really enough crossover that could make everything work a lot better if they were working together."

Student B found meaning in the FW of her particular lab because it inherently combines disciplinary knowledge and skillsets that result in "cool" transformative research outcomes. Based on this statement, it seems that the larger FW of ID is not as present, relevant, or routinely practiced in the disciplines she is bridging, demonstrating siloing between computational, engineering, and biology experimental work. Noticing this, Student B wants to be and is a boundary spanner, filling gaps by learning and utilizing ID knowledge and skills in her research (performance, competence). Motivated by her previous engineering ID research experience, bridging disciplines in her graduate level research in her lab directly contributes to her identity as an ID STEM researcher:

> "Yeah, definitely. I'm, as I've said. Yeah, I'm very glad to have the opportunity to do both computational and experimental work. And I'm glad that my PI fully supports that, and that we have connections, yeah, computationally and experimentally. So I have people on both sides I can reach out to."

Not only does Student B herself recognize, author, and position herself as ID because of her own disciplinary integration behaviors, but also because of the connections built up through her network of support and mentorship, namely her PI, computational experts, and biological experimental experts.

This authoring was further reflected when asked about the influence of the FW of the BII on her ID STEM identity:

> "I do see myself as an interdisciplinary researcher…I feel like I have opportunities to work on a lot of different projects. And yeah, it also provides a lot of different perspectives…Whenever people present their work, they have so many different questions coming up that they might never have thought of."

This response demonstrates that the idea that ID involves the integration of multiple disciplinary perspectives as well as networking and collaborative problem-solving. Student A's view on ID, initially established and developed through her ID engineering experience during her undergraduate career, is sustained and deepened through membership and engagement in the BII (institutional). While less bluntly stated, like Student A, the boundary spanning behaviors, knowledge, and experience gained during Student B's experience in her undergraduate research lab and applied throughout her graduate biomedical engineering program were furthered and mirrored in the FW of the BII (performance), contributing to her recognition of self as an ID STEM researcher.

Overall, these two engineering students bring a strong foundation of knowledge and skills from their undergraduate programs, which can shape their approach to ID research. For instance, their understanding of mathematical modeling, computational methods, or experimental techniques may inform how they tackle complex problems in multiple fields. These students' engineering backgrounds often involves working with colleagues from diverse disciplines, which fosters a unique ability to navigate disciplinary boundaries, and they learn to communicate effectively across different domains and integrate knowledge from various sources. Furthermore, engineers are trained to approach problems in a systematic and analytical way, often using tools like design thinking, prototyping, or simulation. Both students can employ these strategies to tackle complex problems in multiple fields, enabling them to navigate disciplinary boundaries more effectively.

Conclusions and Implications

This work aimed to explore how engineering background in combination with membership and engagement in several FWs influences ID STEM identity formation among engineering graduate students. Our results highlight the importance of considering multiple aspects that affect an individual's identity when evaluating their progress as an ID researcher, including conceptions of ID, disciplinary background, institutional culture and expectations, mentor and peer relationships, and other emerging identities.

The two students inhabit similar FWs that have varying levels of influence on their ID STEM identities. Although the university FW is present, its influence on the students' ID identities appears to be weaker compared to other FWs. The university offers the underlying infrastructure of their graduate programs for the students to mold their own pathways to becoming ID. Within the FWs of the BII and the lab, however, these students take advantage of the resources and networks to augment their ID skills and knowledge, perform and demonstrate their competence, and be recognized for their own intellectual and professional contributions. The BII and the lab have the strongest influence on both students' ID identities, as the students have engaged in extensive collaboration, exposure, and discussion with others across topics and disciplines, and both attribute their self-recognition as ID to engagement in these contexts. It is possible that the lab FW's flexibility and adaptability, combined with the opportunities afforded by the BII in accomplishing its ID mission, as well as the students' own motivations and conceptions of what it means to be ID, have contributed to both FWs' strong influences on the development of ID identities.

In addition to the FWs of the lab and the BII, both students indicated that their disciplines play a significant role in shaping their ID identities, aligned with their other FWs. Student A's discipline inherently integrates across knowledge and expertise, and Student B has acquired ID knowledge through her work in multiple disciplines. The students' engineering experience significantly influences their own recognition as ID researchers, especially through boundary-spanning behaviors, knowledge, and experience gained during their undergraduate research lab and applied throughout their graduate programs and research projects.

This work sheds an important light on how ID STEM identities are shaped and reshaped as engineering graduate student BII trainees traverse intersecting dimensions of their identities. Here we outlined the cases of two students in the same BII who have experience in engineering disciplines, but future research should extend to graduate students in other STEM disciplines and other BIIs or similar ID research centers. Findings contribute an innovative line of research to the fields of STEM identity, science education, and graduate student professional development, and they extend the line of work on how emerging scientists cultivate and attain their identities. We revealed underlying factors of training and education that allow two graduate students to cross disciplinary boundaries, utilize all facets of their academic and personal backgrounds to achieve their goals, and establish themselves with an ID researcher identity. The limited sample size inhibits broad generalization to all graduate students in all BIIs. However, our in-depth analysis of the data from these participants allows us to provide a rich, contextualized account of their experiences and insights.

Neither Student A nor Student B directly mentioned demographic factors as influential to their development as ID STEM researchers, but there is evidence that these factors matter for students' sense of belonging as well as their disciplinary and professional identity development (e.g., [28], [29], [30], [31]). By exploring demographics as influential factors in student identities, future studies can further untangle this complex topic and provide more equitable support strategies for training ID STEM graduate students.

Our data support the idea that innovative programs like BIIs which prioritize ID collaboration could serve as models for graduate programs and across academic contexts to cultivate diverse, inclusive communities. Such approaches help address common graduate challenges like mentorship, recognition of expertise, time management, and work–life balance while supporting students' development as ID researchers and promoting well-being. BIIs and similar ID research centers can provide transformative opportunities to cross traditionally-siloed disciplinary boundaries and combat the current academic culture that prioritizes scientists' mastery of specialized disciplinary skills [36]. Further longitudinal studies can reveal how enduring the impact of ID experiences in these centers is on participants' ID identities and whether over time barriers and opportunities cause participants to return to research practices that separate disciplines. Our study deepens understanding of the complexities of ID research, particularly the potential role of engineering background in ID identity formation, and offers insights to consider when making decisions about program assessment and continuous improvement. Leveraging these tools is essential for fostering ID mindsets and identities among future STEM professionals who could exert an influence on the future of scientific research and knowledge.

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