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Understanding Ecosystems of Interdisciplinary Graduate Education through an Ecological Systems Approach

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Abstract

Responding to decades of calls for interdisciplinary scholars capable of addressing complex societal challenges [1], [2], [3], this conference paper addresses persistent gaps in interdisciplinary graduate education reform. Despite extensive research on transformational interdisciplinary graduate education, little change has been made in reshaping governing funding, policies, and program structures as well as disciplinary-based academic cultures [4], [5], [6]. Moreover, interdisciplinary graduate students, particularly those with STEM backgrounds, still grapple with scholarly identity formation and integration into interdisciplinary research communities [7], [8].

We argue a systems-based approach to evaluating and facilitating interdisciplinary graduate student development– drawing upon Bronfenbrenner's Ecological Systems Theory (EST) and spanning high- and low-consensus disciplines [9], [10], [11]– represents an important answer to calls for systems-based research on multifaceted systemic change across layers of academia [12], [13], [14]. We posit the persistence of challenges in interdisciplinary graduate education results – at least in part – from the primarily localized focus of previous research focusing on only a single domain (e.g., one academic department, only institutional academic policies, and not institutional culture, or on faculty experiences alone), one point in time, and through the lens of primarily sociocultural and cultural-historical perspectives despite calls for systems analyses. Typical research also focuses on learning outcomes, pathways, relationships, identities, and motivations separately (i.e., not as parts of systems or as multiple interrelated aspects of development more broadly) and passively (i.e., typically from the perspectives of faculty and not students themselves) [4], [15], [16], [17].

These research gaps have highlighted the need for systems-oriented research. To that end, this study used Ecological Systems Theory (EST) [9], [18] to examine how dimensions of graduate education interact to influence interdisciplinary students' development across high- to low-consensus backgrounds. This research focused on a qualitative and longitudinal case study of systems influences on interdisciplinary graduate students' development within an interdisciplinary program focused on disaster resilience (referred to as the IDR program throughout). We used a secondary dataset of 62 annual semi-structured interviews with 26 interdisciplinary graduate students across 5 years. A key point of analysis was considering differences between interdisciplinary graduate students' developmental systems and experiences comparatively– specifically across high- (e.g. engineering) and low-consensus fields (e.g., social sciences). Our findings underscore challenges faced by interdisciplinary graduate students across the consensus spectrum and support the idea that interdisciplinary programs where researchers come from disciplinary departments face inherent limitations. This study extends Newswander & Borrego's [19] argument that adding new interdisciplinary degree programs without considering existing organizational cultures and structures can lead to challenges in training interdisciplinary scholars; even in an established interdisciplinary program like IDR, developing interdisciplinary graduate students grapple with the influence of disciplinary microsystems– whether they were engineering or nonSTEM based, and often at the expense of their interdisciplinary work.

Introduction

For at least two decades, U.S. agencies have called for a sustained source of interdisciplinary researchers who can integrate research methods, theories, vocabularies, and cultures across fields. Researchers and educators have responded, aligning graduate settings and curricula to develop this interdisciplinary professoriate [1], [2], [3], [20], [21]. Interdisciplinary graduate programs stemming from these efforts integrate knowledge from multiple disciplines to prepare students to address complex issues like climate change and disasters in their innovative work; examples include environmental studies, bioinformatics, digital humanities, biomedical engineering, and disaster resilience and risk management. Education scholars have explored how to constructively align learning outcomes in interdisciplinary graduate education [22], [23], [24]; how emerging researchers define and experience interdisciplinarity [25], [26]; and how to evaluate interdisciplinary graduate programs and student development in light of their complexity, especially compared to disciplinary counterparts [8], [11], [27], [28], [29]. Researchers have also analyzed various influences on the development of interdisciplinary scholars' identity, motivation, and competencies, primarily grounded in sociocultural and cultural-historical theories of learning [4], [30], [31]. Collectively, these studies have identified individual, relational, social, and cultural influences that impact – and often hinder – interdisciplinary graduate students' development.

Despite this research, little seems to have changed in how we structure graduate education, including funding for these programs and education policies related to it. Interdisciplinary graduate programs still operate within primarily disciplinary-based organizational systems that impact scholars' abilities to engage in interdisciplinary work at the expense of meeting disciplinary expectations [4], [5], [10], [19], [32], [33], [34]. Moreover, students graduating from interdisciplinary programs still struggle to develop positive senses of identity, belonging, and motivation in interdisciplinary research communities– all of which are necessary for pursuing interdisciplinary work as early-career academics [7], [35], [36]. The challenge is particularly acute for graduate students in engineering and STEM (i.e., Science, Technology, Engineering, and Math) fields. These areas of study are considered high-consensus domains, with tightly defined boundaries compared to low-consensus fields, such as the humanities and social sciences, with more flexible disciplinary cultures around knowledge creation. STEM fields, especially engineering fields, are marked by highly constrained curricula, sources of research funding, and types of knowledge that can be developed within disciplinary boundaries. As Lindvig [8] found in their study of interdisciplinary doctoral students' development, these high-consensus disciplines also often limit opportunities for interdisciplinary exploration, impinging upon developing interdisciplinary researchers' persistence in interdisciplinary research careers [6], [8], [10], [11], [31].

Together, scholars suggest that as researchers seeking to understand interdisciplinary graduate student development, we have to recognize interdisciplinary graduate students' learning is deeply impacted by siloed institutional epistemic cultures, as well as the multilayered systems of structures in higher education that they are embedded within [4], [12], [13], [14], [29], [36], [37], [38], [39], [40]. Considering the multiple different settings that interdisciplinary graduate students span as overlapping and interrelated systems is a critical lens for gaining a deeper understanding of how multiple cultural systems interact in the context of interdisciplinary education and how these systems impact student development– but systems studies of this development are lacking in the literature at this point. Additionally, while we have a good understanding of how these kinds of dynamics impact faculty and impact students from the perspectives of faculty, we know a lot less about what the cultures of (inter)disciplinarity as well as the systems that uphold and (re)produce these cultures mean for graduate students' development from the perspectives of students themselves, and we also know little comparatively across students' disciplinary backgrounds (i.e., high versus low consensus graduate student experiences).

In this paper, we argue that the persistence of challenges in facilitating interdisciplinary graduate student development results – at least in part – from the localized focus of much of the previous research, with individual studies generally focusing on only a single aspect of interdisciplinary graduate student development (e.g., identity, motivation, competency development), a single domain (e.g., one academic department, only on institutional academic policies and not culture), on primarily faculty's perspectives at the expense of graduate students, or one point in time (i.e., cross-sectional studies), as well as through the lens of primarily sociocultural and cultural-historical perspectives of learning alone despite calls for systemic change. To illustrate, Lindvig's [8] study of students and faculty in interdisciplinary graduate programs in Denmark did not look across relevant settings and contexts outside the program. Similarly, Holley's [7] study provides a longitudinal example of graduate students in an interdisciplinary neuroscience PhD program, but it does not address system-level issues or interdisciplinary perspectives outside of neuroscience. Much-existing research also relies on the perspectives of faculty alone– where interdisciplinary graduate student development is something being facilitated, not experienced. This is the primary perspective represented in Welch-Divine et al.'s [5] report on facilitating interdisciplinary graduate education, Boden and Borrego's [4] analysis of academic and organizational barriers to interdisciplinary research from a faculty lens, and Wallace and Clarke's [41] analysis of barriers to interdisciplinary environmental studies. Though we know faculties' experiences in interdisciplinary work are inextricably linked to their engagement in interdisciplinary graduate programs and to their graduate students' development [19], [42], we also have to address scholars like Graybill et al. [17], who wrote,

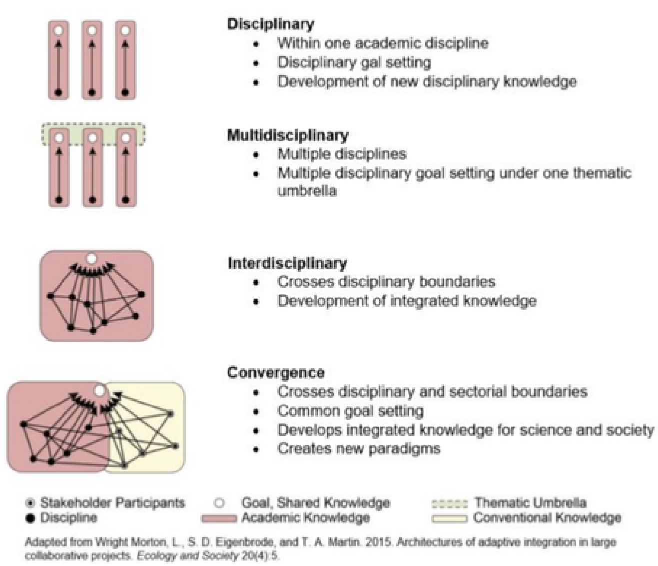
> Innovative interdisciplinary research and curricula have been created to train a new generation of scientists to engage with complex issues. It seems critical that those most affected by interdisciplinary education—doctoral students—provide feedback about such innovations. Without understanding students' experiences in interdisciplinary programs, faculty will not know whether they are "getting it right" for future generations of interdisciplinarians (p. 757).

Given the persistent challenges of interdisciplinary graduate education, scholars have consistently called for multifaceted, systemic change across the layered systems of academic institutional governance and the incentive structures both inside and outside of universities to institutionalize interdisciplinary and better facilitate interdisciplinary researcher development, but calls for systems research in this space have been left largely answered [4], [12], [13], [14], [29], [36], [37], [38], [39], [40]. Such change, we argue, would benefit from a study that uses a systems approach to study interdisciplinary graduate student development spanning varied academic systems and structures, viewing them as interrelated parts of a complex ecosystem that changes over time, as well as one that compares the influences of these settings on students across epistemically divergent fields from the perspectives of graduate students themselves. In this way, our study expands the literature base on interdisciplinary graduate student development to include more systems analysis of the influences on this development across multilevel settings, structures, cultures, and time. This kind of research represents an important first step into more comparative research across institutional settings and organizational structures related to interdisciplinary graduate programming using Ecological Systems Theory to identify potential leverage points for aligning the multiple intersecting and layered systems impacting these students' development.

Theoretical Framework

In scoping this research, we operationalize two terms– *interdisciplinarity and human development*. In the context of interdisciplinary education research, scholars such as Latucca [25], Klein and Newell [12], and others [26], [37], [43], [44], [45], [46], [47], [48] have sought to distinguish terms such as multidisciplinary, interdisciplinary, transdisciplinary, and more recently convergence. Figure 1 illustrates generally accepted distinctions; it was adapted from Wright-Morton et al., [47] and taken from the Department of Psychiatry and Behavioral Sciences at Northwestern Medicine website.

Figure 1: Definitions of Disciplinary, Multidisciplinary, Interdisciplinary, and Convergence



In practice, however, these distinctions are often fuzzy. Within the interdisciplinary graduate program analyzed in this study, interdisciplinary graduate education was characterized more generally by learning that integrated diverse academic disciplines and stakeholders' knowledge, values, and approaches to answer research challenges not satisfactorily addressed by a single discipline alone. Learning was driven by authentic, compelling problems that arose from both deep disciplinary questions and pressing societal needs; problem-focused learning encouraged students to innovate by synergizing diverse perspectives with totally unfamiliar ones. The program thus aligned philosophically with the definitions of interdisciplinarity aspiring towards convergence. At the same time, students in the IDR program still obtained degrees from and conducted dissertations within traditional disciplines. While the program's design worked to expand students' knowledge and perspectives across disciplinary boundaries, students' practice of integration within their research varied widely. Most of the researchers involved in the IDR program were still housed within disciplinary departments, possessed or sought disciplinary degrees, and responded to disciplinary supervision and assessment. Graduate students had to complete their dissertation within a home disciplinary department, though a requirement of IDR was including at least one interdisciplinary faculty member (i.e., one professor outside of students' home disciplines) on IDR theses/dissertations. Thus, while the IDR program sought interdisciplinarity in the terms defined in Figure 1, in practice it included work that was also disciplinary and multidisciplinary. These dynamics make the IDR program an ideal site to study the tensions developing interdisciplinary scholars face when navigating the interrelationships between academic systems.

To operationalize interdisciplinary graduate student development, we used Bronfenbrenner's definition of human development. In his Ecological Systems Theory (EST), Bronfenbrenner described the process of human development as involving:

> A progressive, mutual accommodation, throughout the life course, between an active, growing human being and the changing properties of the immediate settings in which the developing person lives… as this process is affected by relations between these settings, and by the larger contexts in which the settings are embedded [9] (p. 107, original italics).

Bronfenbrenner described these settings where people develop in terms of ecological systems and posited that:

> [Development occurs when a person] acquires a more extended, differentiated, and valid conception of their ecological environment, and becomes motivated and able to engage in activities that reveal the properties of, sustain, or restructure that environment at levels of similar or greater complexity in form and content [18] (p. 27).

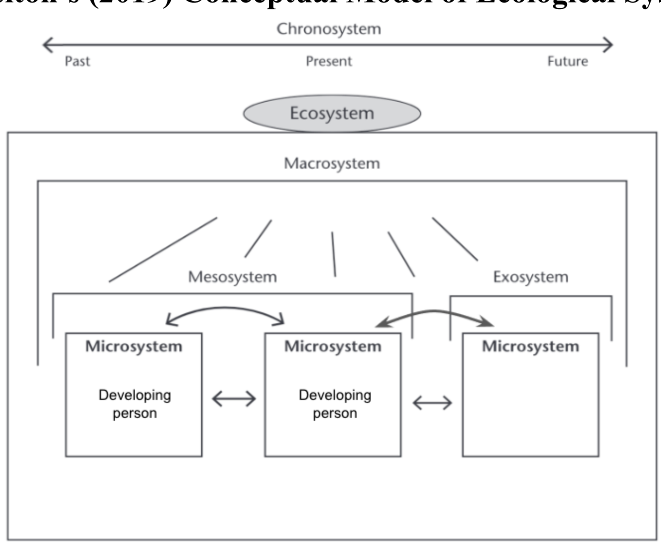
In other words, Bronfenbrenner posed development as a dynamic and ongoing process that involves mutual interactions between individuals and their environment, highlighting both bidirectional influences as well as changes that occur over time. EST defines development as humans gaining a more 'valid and differentiated view' of their environment, the skills and motivation to maintain it, adapt to it, and even restructure it to make it meet their needs more effectively. By valid, extended, and differentiated, Bronfenbrenner suggested these aims entail a deeper and more accurate understanding of the intricacies of both their immediate and extended environments [9], [49]. Through engagement with activities, relationships, and roles, people develop a heightened awareness that empowers them to further engage in activities that reveal the inherent properties of their environment and extend their worldviews as well as provide opportunities for discussions that promote nuanced insights and rectify potential misunderstandings. Importantly, this definition of development integrates multiple aspects of personal background, identity, motivation, and competency development into one definition.

Integrating these two terms, then, we defined interdisciplinary graduate student development in our study as

> The process through which [an interdisciplinary graduate student] acquires a more extended, differentiated, and valid conception of [interdisciplinary research and practice], and becomes motivated and able to engage in activities that reveal the properties of, sustain, or restructure [that domain] at levels of similar or greater complexity in form and content. [18] (p. 27).

In more detail, Ecological Systems Theory posits development as a process involving individuals' increasingly extended and differentiated participation in, as well as a valid understanding of, activities, relations, and roles in multiple layers of their academic environment. In the context of graduate education, these can include things from courses to departmental policies and procedures, to university structures and national research agencies; they can also include relationships with peers, faculty, and other significant actors in their academic environment as well as the expectations of the roles these students and others take on when in these spaces [50]. At the heart of the EST model for human development is the developing person, along with their attributes, interests, and goals, as well as previous experiences, meaning that students are not blank slates when they enter school and are rather agents of change with an entire life history. However, EST also proposes that developing individuals are embedded in multiple nested environmental systems, ranging from the microsystem (i.e. students' immediate surroundings, such as classroom setting and peers) to the macrosystem (i.e., larger cultural and societal influences around knowledge-making). These systems all interact to shape a person's development just as people themselves have agency and effect over these systems [18], [49], [51], [52], [53]. Though EST is often depicted as a set of nested circles with the microsystem as the innermost system and the macrosystem as the outermost, in this study we use Shelton's [54] model, adapted and shown in Figure 2. This visualization illustrates how EST's five layers of an individual learner's environment– microsystems, the mesosystem, exosystem, macrosystem, and chronosystem– are different not merely in scope or size.

Figure 2: Shelton's (2019) Conceptual Model of Ecological Systems Theory



Note. Adapted from Shelton (2019)

For this conference paper, we honed in on EST's construct of microsystems and specifically how IDR graduate students' mesosystem-level microsystems impact their development. EST posits that individuals directly or indirectly participate in a variety of different microsystems, where a microsystem is a "pattern of activities, roles, and interpersonal relations experienced by developing people in given settings with particular physical and material characteristics" [55] (p. 227). In graduate school, the different settings students operate within as they develop contain microsystems that can include interactions with advisors and peers, departments, as well as activities like coursework, research projects, and extracurricular projects related or unrelated to their field of study; they can also include students' relationships with family members within their home, as well as with coworkers and a supervisor within a place of employment [50], [53], [56], [57]. These different interacting settings (and their microsystems) contain various patterns of or expected, appropriate kinds of activities, roles, and relationships. From this view, these patterns, as well as salient material and physical characteristics of microsystems, collectively shape graduate students' day-to-day experiences and contribute to their overall development as interdisciplinary scholars. Importantly, these patterns also tend to support certain kinds of development and inhibit others.

We argue that comparing microsystems and students' relationships with them across engineering-based (high-consensus) and non-STEM-based (low-consensus) interdisciplinary graduate students' experiences is of particular interest based on research suggesting the academic environments, structural and cultural, associated with disciplines ranging from high- to low-consensus fields have unique impacts on developing interdisciplinary researchers that, when compared, can shed light on pathways for change; we, as well as other researchers, posit this kind of work is of particular interest to high-consensus fields [6], [8], [10], [11]. In doing this work, we believed that there might be patterns in IDR program graduate students' development trajectories that support some kinds of interdisciplinary scholars over others.

EST also suggests human development is impacted by interrelationships among microsystems. The mesosystem captures these linkages between microsystems, which are often graduate students' mentors and advisors [50]. EST posits that a mesosystem will support development to the extent there are *supportive* linkages between varied settings, as students' relationships with people who span various microsystems inside and outside of a students' mesosystem (i.e., direct surroundings) provide opportunities to discuss, share, question, extend, and validate students' understandings of their experiences [9], [58]. A mesosystem is considered developmentally supportive when its microsystems support each other and when the developing person has valid and differentiated information about these microsystems. In the context of graduate education, more differentiated information often comes in the form of exposure to new academic departments, programs, faculty, and administration within a given institution over time. Differentiation of microsystem experiences in the mesosystem enables graduate students to compare different systems, expand their understanding, and correct misconceptions to establish increasingly valid information about the overall ecosystem [18], [54]. We argue therefore that analyses of interdisciplinary graduate students' microsystems involve not just understanding the microsystems themselves but also the relationships between them and how those relationships impact students' too.

Like the mesosystem, Bronfenbrenner's exosystem focuses on interactions among microsystems but focuses on links between microsystems when at least one microsystem is one in which the developing person does not directly participate [54]. In this conference paper, however, we are not focusing on these indirect microsystems (i.e., exosystems) or the macrosystem and chronosystem constructs associated with the entirety of EST. EST, even broken into its components, provides a useful theoretical framework with the vocabulary for describing how aspects of interdisciplinary developmental ecosystems function and why they function that way, as well as for considering changes that can make settings more or less desirable for supporting interdisciplinary researcher development. Focusing on direct microsystems making up interdisciplinary graduate students' mesosystems helps simplify this initial analysis across high- to low-consensus fields. By focusing on microsystem influences first, this research helps confirm the applicability of EST to our context and the ability of our methods to garner significant answers to our research questions. As such, this conference paper represents only a first step towards a more holistic analysis of the IDR program ecosystem ranging from microsystems to the macrosystem and chronosystem. To date Ecological Systems Theory of Human Development has not been applied to analyze interdisciplinary graduate education environments except in one of our pilot studies [50], making this a novel approach.

Purpose Statement and Research Question

We used Bronfenbrenner's Ecological Systems Theory (EST) of human development to examine how multiple systems and settings of graduate education interact to impact graduate students' development as interdisciplinary scholars. This research took the form of a single longitudinal qualitative and embedded case study of an NSF-funded interdisciplinary graduate program in disaster resilience (the IDR Program). We analyzed a secondary dataset of annual interviews with student participants where key points of consideration were differences between high-consensus disciplines (i.e., engineering) versus low-consensus ones (i.e., humanities and social sciences). Using the lens of EST, we explored salient systems influences on graduate students' development as interdisciplinary researchers and the ways systems and their interrelationships facilitated or hindered the developmental potential of the IDR program. Using existing data in an embedded case study design to investigate variations between interdisciplinary graduate students' development in Engineering (ENG) and non-STEM (nonSTEM) fields, this study focused on this research question:

RQ 1. How can direct microsystems influence graduate students' interdisciplinary development similarly and differently, comparing students with backgrounds across engineering and non-STEM fields?

Our answer sheds light on a dynamic ecology of interdisciplinary graduate student development as well as what kinds of aspects of engineering-based and non-STEM-based interdisciplinary graduate students' academic ecosystems need to be addressed (and how) to push the slow-moving needle of interdisciplinary graduate education. Although this research is a single-case study, it represents an important first step in gaining the perspectives we need to systematically design interdisciplinary graduate programming in a way that aligns with and capitalizes on the complex nature of various interdisciplinary graduate students' development. Centering our study on one ecosystem at a time is also beneficial for distilling meaning from a study using Ecological Systems Theory [9] to understand an already complex set of systems such as those associated with interdisciplinary graduate education.

Methods

Project Background

Secondary data for this study came from an interdisciplinary graduate certificate program called the Interdisciplinary Disaster Resilience (IDR) program. The IDR program was located in a land-grant university in the mid-Atlantic region of the United States. It was funded through the National Science Foundation Research Traineeship (NRT) program and grew out of an existing collaboration that created a university-funded interdisciplinary graduate program. As mentioned, though this program granted interdisciplinary graduate certificates, most IDR researchers were still housed within disciplinary departments and managed disciplinary-based expectations.

Participants

To date, 91 semi-structured interviews with 36 IDR interdisciplinary graduate students including consent for research have been collected for program assessment across the 5 years (2019-2023) of NRT grant funding; this secondary dataset of interviews made up the basis data of this study. See Table 1 below for a breakdown of the number of students over these five years.

Table 1: IDR Program Consented Student Interview Numbers (All Disciplines)

Cohort (start year)	N for Year 1 (2019)	N for Year 2 (2020)	N for Year 3 (2021)	N for Year 4 (2022)	N for Year 5 (2023)
Cohort 1 (2019)	9	8	7	4	3
Cohort 2 (2020)	NA	6	5	4	4
Cohort 3 (2021)	NA	NA	11	8	6
Cohort 4 (2022)	NA	NA	NA	5	4
Cohort 5 (2023)	NA	NA	NA	NA	7
Yearly Subtotals	9	14	23	21	24
TOTAL			91		

For this particular conference paper, we are focusing on a subset of these 91 interviews coming from 36 students– only engineering-based and non-STEM based interdisciplinary graduate students in the IDR program. Specifically, we focused on the 62 interviews coming from 26 interdisciplinary students whose home disciplines include civil engineering (CEE), mechanical engineering (ME), computer science (CS), industrial and systems engineering (ISE), as well as non-STEM fields including urban affairs and planning (UAP) and sociology (SOC). We focused on engineering and non-STEM graduate students in particular to highlight more distinct perspectives and experiences within these more extreme high and low consensus disciplines. Examples of STEM fields represented in the IDR program that were not engineering and therefore not included in this study were Geosciences (GEOS) and Fish and Wildlife Studies (WFS). Table 2 below includes a breakdown of all IDR Program graduate students in terms of Engineering (ENG), STEM but not Engineering (STEMnonENG), and non-STEM (nonSTEM) groups. In total, there were 17 engineering, 9 STEM but not engineering, and 10 non-STEM interdisciplinary graduate students, but again– this conference paper focuses just on the perspectives of the 26 engineering and non-STEM graduate students. From these groups, we had 36 interviews for engineering-based IDR grad students, 26 interviews for STEM but not engineering-based students, and 29 interviews for nonSTEM-based students (giving a total of 91 interviews and 62 specifically from engineering and non-STEM students). Given the small number of students from any single department, we do not further identify participants.

Table 2: *Disciplinary Breakdown of IDR Student's Home Disciplines*

Participant ID	# Interviews	Domain
A	3	ENG
I	3	ENG
L	1	ENG
N	4	ENG
P	2	ENG
Q	1	ENG
T	3	ENG
U	3	ENG
V	3	ENG
W	3	ENG
Z	1	ENG
AC	2	ENG
AD	1	ENG
AG	2	ENG
AI	2	ENG
AL	1	ENG
AM	1	ENG
TOTAL ENG	36 interviews	17 participants
B	3	nonSTEM
E	1	nonSTEM
F	5	nonSTEM
G	5	nonSTEM
K	4	nonSTEM
X	2	nonSTEM
AB	2	nonSTEM
AF	2	nonSTEM
AJ	2	nonSTEM
TOTAL nonSTEM	26 interviews	9 participants
C	2	STeM nonENG
D	4	STeM nonENG
H	5	STeM nonENG
J	4	STeM nonENG
O	4	STeM nonENG
S	3	STeM nonENG
Y	1	STeM nonENG
AA	3	STeM nonENG
AE	2	STeM nonENG
AK	1	STeM nonENG
TOTAL SteM (not Engineering)	29 interviews	10 participants
TOTAL ALL	91 interviews	36 participants

Data Collection: Secondary Semi-Structured Interviews

Student participants were interviewed annually, yielding up to as many as 5 interviews for Cohort 1 students and as few as 1 interview per graduate scholar for those in Cohort 5. On average there were 3 interviews per student. All interviews were conducted by three of the program's graduate research assistants– all educational researchers who have observed and taken courses in the program, as well as have built significant rapport with the participants over time. Questions in our interviews primarily focused on student experiences in their interdisciplinary program and what pupils found to be helpful and challenging about their academic environments and their development as interdisciplinary researchers. The primary data for this specific study came from students' answers to the questions, "What has supported you in your journey to becoming an interdisciplinary scholar?", "What pieces of the program would you like to see changed?", and "Are there pieces of the program that have helped or hindered your progress?" [50], [59].

Regarding the use of this secondary dataset to answer our research question, the main limitations are primarily related to intent [60], [61] because our dataset was not collected originally to answer our specific research questions or using reflexive thematic analysis in particular. Instead, at the outset of our work, this dataset's collection was informed by a general semi-structured interview protocol design and was focused on program assessment and interdisciplinary scholars' experiences in the IDR program in a broad sense. Our research groups' initial plans for these student interviews included tracking students' interdisciplinary graduate student identity development and motivation towards this development longitudinally. We were searching for individual, cultural, and structural supports and barriers to this sort of identity-based motivation in our work [62], [63], exploring the links between how graduate students see their identities as interdisciplinary scholars and how these perceptions influence their interdisciplinary development and program engagement [59], [64]. That said, in our previous research studies on this dataset where we tried coding grounded in Future Possible Selves Theory [62], [63], [64], [65], [66] as well as Social Cognitive Career Theory [67], [68], [69], [70], [71], [72], [73], we became dissatisfied with assuming a binary between supports and barriers as internal or environmental conditions that either enhance or impinge upon students' identity development alone, noticing that this forced deduction and classification of identity development as separate from students' motivation, existing competencies, and skill development failed to capture all the complex dynamics interdisciplinary graduate students were discussing in their interviews. Additionally, we also learned that supports and barriers across different aspects of students' experiences to students' development were not mutually exclusive [59], [64] ; students were talking in terms of identity, motivation, and skill development as well as interrelated influences on these constructs all at once in our interviews– making studying identity development alone nonsensical. Since then, we have successfully shown EST salient in the experiences of interdisciplinary graduate students' development and as an effective lens for unpacking the nature of graduate student development discussed within our secondary semi-structured interview dataset [50]; this provided a basis for our confidence in this work.

Data Analysis

Once the audio-recorded interviews from students were transcribed by a professional transcription service, we analyzed the data via Reflexive Thematic Analysis (TA) [74], [75], [76], [77], [78], a qualitative method characterized by its six phases that are distinct yet recursive– ***phase 1.*** *data familiarization,* ***phase 2.*** *data coding,* ***phase 3.*** *initial theming,* ***phase 4.*** *theme review and development,* ***phase 5.*** *refining, defining, and naming themes, and* ***phase 6.*** *writing*.

Our approach to reflexive thematic analysis moved between more inductive and deductive modes, and from an initially semantic to a latent focus [75]. As Braun and Clarke define it, latent coding involves systematic analysis that goes beyond explicit content, aiming to identify underlying concepts, patterns, and thus themes that are not at first apparent; it entails interpreting data to uncover the implicit, or hidden, meanings and insights in a particular text. We analyzed this secondary dataset in repeated and systematic movements between these different phases in a spirit of inquiry and interpretation toward answering our proposed research questions [79], [80], [81], [82], [83], and viewed our reflection and active roles as both researchers and IDR program members as crucially important to addressing the inevitable subjectivity of the Qualitative paradigm.

Specifically, we first established Familiarization based on identifying the influences (i.e., activities, relationships, and expected roles) on interdisciplinary graduate student development. It is important to note that though we employed longitudinal interviews– offering us a perspective on IDR students' microsystems for a prolonged duration– in the analysis we treated interviews from each student and then the students as groups as effectively cross-sectional, 'lumping' student interviews and neglecting the analysis of how microsystems might change in time. Then, we went back and coded inductively for discrete units of influences (various activities, relationships, roles, and settings) on interdisciplinary graduate student development in the words of students (or with an assigned code based on the semantic meaning in participant's words), separating the data relevant to this study's research question form extraneous information [74], [75], [82], [84], [85]. After, we coded these instances of influences deductively according to an a priori coding framework based on EST (i.e., microsystems, mesosystem, exosystem, macrosystem, chronosystem, interactions between layers) to categorize them [9], [74] as elements of various layers/elements of interdisciplinary graduate students' surrounding ecosystems. Aligned with the proposed research question of this study, we segmented out only data relevant to the microsystem and mesosystem elements of EST for our next analysis phases. At this point, our goal was to achieve an initial categorization of the salient direct microsystem influences on interdisciplinary scholar identity development from the perspective of IDR graduate students. We also separated the perspectives of students with engineering backgrounds and nonSTEM backgrounds from each other at this time.

Moving into Phase 3 Reflexive TA, which involved initial theming (followed by Phases 4 and 5 which involved theme review and development (Phase 4) as well as refining, defining, and naming themes (Phase 5)), our next goal was to provide an in-depth interpretation of the meanings of these various groups of students' reflections on their developmentally-relevant microsystem dynamics– first as groups and then as scholars coming from high- to low-consensus disciplines compared to one another. To accomplish this, we took our strategically segmented data and established the most salient microsystems across our two groups of IDR Program interdisciplinary graduate students' discussions. Note that this involved ignoring settings, activities, roles, and relationships that individual students within a group considered part of their developmental ecosystem as these do not constitute the overall groups' experience– this introduced a limitation of generalization into our study so that we might identify wide-reaching issues. Once we had an idea of what these most salient microsystems were, we analyzed looking for how the expected activities, roles, and relationships within them impacted students within our groups of engineering and nonSTEM students. We then compared these microsystem dynamics across their disciplinary backgrounds to answer our research question. After exploring the mechanics of the microsystems, as well as unpacking how influences identified vary across the experiences of IDR program interdisciplinary graduate students' whose disciplinary homes are Engineering (ENG) and nonSTEM fields, we started writing. We sought to not just provide a list of what the microsystems are and what they contain, but rather how they work (as well as how they are expected to work), how their interrelationships matter, and what this all means for interdisciplinary graduate students' development across disciplinary backgrounds.

Reflexive TA as defined and practically guided in Braun & Clarke's most recent book [75] is a method well-aligned with the goals of this study, the nature of our data, as well as the types of iterative and open-ended approaches necessary to capture the complexity of interdisciplinary graduate development. The theoretical flexibility of this method, as highlighted by a variety of scholars across disciplines (including but not limited to Bryne [81], Hayfield et al. [86], Guest et al. [87], Kjaran & Jóhannesson [88] and Lester et al. [89]), allows for both inductive and deductive analysis across different types of coding and theories. This is especially important for our large and diverse data set, which was not collected with our specific theoretical framework in mind. The method allowed our study with a secondary dataset to still be informed by Ecological Systems Theory [9] in the interpretive stages of analysis to explore the "rhetorical strategies deployed by participants and establish the truth claims of their commentary" [78] (p. 17) [88]. Reflexive TA is known for its proclivity towards the analysis of large and multivariate datasets [84], as well as its ability to capture complicated interactions through inductively oriented experiential analysis on patterned meaning [86], [90] making this approach highly relevant and suitable.

Findings

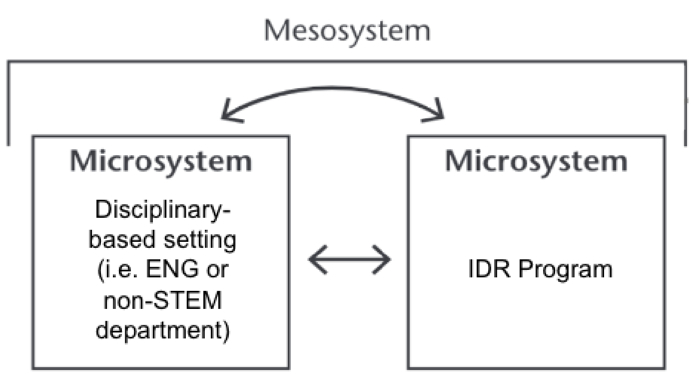
At the outset of this study, we wanted to open up systems analyses of interdisciplinary graduate student learning and graduate education, seeking to understand how various settings (as well as their patterns of expected activities and interrelationships) developing interdisciplinary scholars interact within influence their development. In our analysis, we compared the experiences of IDR Program students with engineering and non-STEM backgrounds, seeking common themes in these groups' narratives of their continued engagement in increasingly complex interdisciplinary work as well as how their development was impacted by both similar and different sets of appropriate activities, roles, and relationships students as they pursue interdisciplinary work in graduate school. The following section first overviews the common aspects and impacts of IDR graduate students' microsystems overall, then it discusses the differences between engineering-based and non-STEM-based students' microsystems and their interrelationships as impacts on interdisciplinary graduate student development.

RQ 1: How can direct microsystems influence graduate students' interdisciplinary development similarly and differently, comparing students with backgrounds across engineering and non-STEM fields?

Common or shared aspects and impacts of IDR graduate students' microsystems across high- and low-consensus disciplines

In the context of the IDR program, interdisciplinary graduate students'– with background disciplines spanning engineering and non-STEM fields– continued engagement in increasingly complex and expanded interdisciplinary work (i.e., their development as interdisciplinary scholars through the lens of EST) was most significantly impacted by two interrelated settings. They included the IDR graduate students' home disciplinary departments' settings (whether that be an engineering or a nonSTEM department's setting) and their associated microsystems– the expected patterns of activities, roles, and relationships for graduate students within them– as well as the IDR programs' own set of appropriate patterns of these things. Figure 3 depicts the common architecture of IDR Program interdisciplinary graduate students' two direct microsystems within their mesosystem. The microsystem box on the left represents either the engineering or nonSTEM-based IDR graduate students' disciplinary departmental settings and the one on the right represents the IDR Programs'. The connections between these direct microsystems represent the interrelated nature of these two as parts of students' overall mesosystems.

Figure 3: IDR Grad Students' (Engineering and nonSTEM) Micro- and Mesosystem Architecture



In more detail, IDR Program graduate students' development (i.e., all students across both engineering and nonSTEM fields) was most impacted by both their home disciplinary departments' microsystem (whether it was an engineering or nonSTEM one) as well as the IDR programs' microsystem. These microsystems consisted of similar patterns of appropriate activities like course requirements, theses, dissertations, and their committees, as well as managing the roles and relationships associated with being both disciplinary and interdisciplinary graduate students working alongside advisors to finish these activities. Continually, interdisciplinary graduate students across high and low consensus backgrounds discussed the role of coursework, completing a thesis/dissertation, and doing so alongside their advisor as critical elements of their development as interdisciplinary researchers (perhaps as expected), but they also suggested that these expected activities, roles, and relationships existed within distinct, overlapping, and interrelated spaces– that of their home disciplinary department and that of the IDR program. These settings came with, albeit similar, different kinds of patterns of expectations for graduate students that often stood in conflict with each other, thus impacting students' continued engagement in interdisciplinary work. Additionally, ultimately students' disciplinary departments' expectations outweighed those disciplinary expectations within the IDR program as participants in this study, despite pursuing interdisciplinary research, were still housed within disciplinary departments, sought disciplinary degrees, and responded to disciplinary supervision and assessment. This dominance of disciplinary microsystems over the interdisciplinary ones represented a key feature of the salient interrelationships between microsystems on IDR program graduate student development. In practice it meant that the IDR programs' requirements for having an interdisciplinary advisor and of taking additional interdisciplinary classes were considered voluntary or additional on top of classic disciplinary-based requirements for graduate students.

Student AC (2022) described these additional IDR requirements well, saying,

> One of my committee members was outside of my home discipline, because that was a requirement of being in the program. I also had to take courses outside to cover interdisciplinary topics that added onto my PhD requirements overall. Sometimes it has been hard to manage.

Student A (2020, 2019) added to this and said,

> So I was thinking about the [IDR] program, and I think it is a little bit hard to be motivated, because PhD students need to be the first author of their dissertation in their disciplinary department. And everyone is a PhD student so it is hard to collaborate. That means one or the other should be a second or third author on that project. So, their priority cannot be that interdisciplinary project. Because of that feeling, I think it is hard to be motivated to collaborate with different interdisciplinary students. And I also get faculty have similar feeling, because they have their own discipline issues projects. So, I think the [interdisciplinary] projects became not a priority. It became a secondary or third thing they needed to do. So, if we want to be motivated, I think there needs some force that's pushing students to do that as a requirement. If you are [an IDR] student, you need to do one interdisciplinary project like this. PhD students, if there's a requirement like that, it will be hard and it will be extra work, but I think without those kinds of requirements, it will be the same for the entire five years or next three years. Because if there's no flexibility in requirements they want to do, but it's hard to do in this circumstance, in this system. PhD students need to be first authors. That's the hard part. Like it's kind of the existing structures make it difficult.
>
> Because I have some experience in the research institute, if I work alone, I cannot make or find novel findings, or some synergy effects, so I know the importance of teamwork and the power of synergy and team working, so ... But as a PhD student, because I think it's a kind of becoming independent research, researchers, so in that perspective, collaboration ... 100 percent collaboration research is not a good policy or a good thing during a PhD student. This is my opinion, but … I think it's for every PhD and for every discipline. So that's a little bit ironic of IDR.

Despite these two students'– as well as many others'– struggles with added requirements and issues making the IDR program work when disciplinary-based requirements take precedence, Student AK (2023) and other also mentioned the value that many IDR scholars still saw in taking on extra work in the form of IDR course work to gain interdisciplinary perspective they would not have otherwise. Student AK said,

> This semester [in the IDR program] was challenging and enriching. Because there were sociologists. There were history grad students. There were engineering grad students. There were hard science students. So that was really interesting because my other interactions over my masters, my undergraduate, it's pretty much all been people from the social sciences. So it was a very, very new challenge to be in [NAME]'s course. The first lesson in the fall, we had really interesting speakers… Let's see…Also, using the word, "force," is not the right word, but kind of forcing our hand to interact and kind of pulling us into discussions when it's challenging because going into something transdisciplinary, multidisciplinary, etc. again, it was way outside of my wheelhouse, which I wanted, but there was a lot of times where the sociologists, because there were other sociologists in the course, were discussing things that were way outside of how I conduct research, way outside of how I write or think of things, but she was good at pulling all of the other disciplines into the discussion. Plus, [NAME] she is just-- she's a great speaker, and she almost demands the attention of the room just being who she is. And so she really helped pull the class together, as challenging as that was. Most classes that I'm always in are a bunch of other people in my discipline, and so it's easy for us to communicate. We all have the same language. So [NAME] was really good at also teaching us the interdisciplinary language too. We talked a lot about the language of what things are called in different disciplines, and we talked about the difference between the definitions of things like hazards, disasters, etc. etc. and we really started to-- we really began the class focusing on how for all of us to discuss it together and then moved into other things after that. So she constructed it really well.

Adding to this, Student K (2023) provided input on the value of having additional committee members outside of their discipline in dissertation and thesis work.

> So I had this experience to work with Dr. [NAME] as my committee member, and I think it was a great experience and I am happy that, actually, DRM required us to have a committee member from the core faculty members in DRM. It was very good because he had a kind of different perspective and he provided me some insights that I haven't thought about before, so I am very happy that I had this chance to have him in my committee and I could include maybe some sides from other disciplines in my dissertation. Other than this, I didn't have much experience working with faculties from other departments. So I think that this is my only experience of working with the faculty from other than my own department. What was particularly useful was– my dissertation was very focused on extreme heat, so I looked at this problem from the narrow perspective of the planning. But throughout, for example, the oral preliminary exam, he actually asked some questions that made me actually think about it. For example, he asked me, "So what's the difference between-- when you are talking about heat mitigation strategies, what's the difference between the adaptation and mitigation or have you thought about maybe including other kinds of strategies other than the planning-related mitigation strategies? So what about, for example, business? What about the economy? What about the policy-related heat mitigation strategies?" So I think that that was very important and very useful to make me realize about those other aspects in my dissertation (Student K 2023).

That said, Student Z (2021) shed light on the kinds of challenges that can arise for interdisciplinary graduate students seeking consensus around research amongst faculty members spanning disciplinary backgrounds and their diverse expectations for scholarship and milestones in graduate school.

> Balancing my research between disciplinary and interdisciplinary is very challenging. Especially at the beginning it was so challenging when I started. But over time I mastered it. But how I make it balanced, I think that first we don't – helping the professor, I mean that the advisor is not possible. I cannot work without – collaborating the multidisciplinary work without helping from – having help from my supervisor

> and his support. I think that the support of the professor is very important. And you know I have a qualifying exam, and when – during my qualifying exam when I start to say some words from both of my disciplines my committee members say that oh, perhaps this is out of our scope. Or why are you going to discuss that? And then the justification is a little hard, and at that time for example I had the support of my professor. Then I think that at the – and another thing is that because I – for example first I focus on my discipline. I think that at that time I am – OK, I have enough background in my discipline (Student Z 2021).

Taken together, these quotes pointed to the idea that the IDR program microsystem, and its patterns of activities, roles, and relationships related to interdisciplinary course and committee member requirements introduced complexity into graduate students' lives because of the added nature of IDR program requirements on top of their disciplinary-based degree milestones. Though students found value in engaging in these additional requirements, our student interviews suggest that the onus and incentive was put on IDR students themselves to pursue the additional activities, roles, and relationships associated with developing as interdisciplinary scholars because of the nature of their university's organizational structures. This ultimately meant that, even though IDR students found value in the program's added requirements supporting their development by exposing them to new perspectives and challenging them to take on work that would not typically be possible in the context of their home discipline, the lack of overall alignment between microsystems within students' broader mesosystem (i.e., between disciplinary-based program requirements and interdisciplinary-based program requirements), as well as the dominance of disciplinary-based microsystem structures over interdisciplinary ones (i.e., the uneven interrelationship between the microsystems) impacted students' motivation to continue engaging in interdisciplinary research.

Differences in IDR graduate students' microsystem dynamics and interrelationships comparing impacts across high- and low- consensus fields

Though IDR Program graduate students across high- and low- consensus backgrounds could agree that their interdisciplinary program microsystem's requirements were added to their departmentally-based ones and that their interrelationships were characterized by disciplinary requirements often taking precedence (making it challenging to be incentivized to continue pursuing interdisciplinary work)– the ways in which the IDR Program's microsystem and their departmental microsystems impacted students from engineering versus non-STEM backgrounds also differed from each other.

The critical ways in which engineering versus nonSTEM microsystems' patterns of expected activities, roles, and relationships differed from each to impact interdisciplinary graduate students' development were aligned with these divergent disciplines' as defined as high versus low consensus. For decades, scholars of interdisciplinarity have considered engineering to have high levels of consensus with respect to terminology, methods, and important research questions– especially in contrast with social sciences and humanities disciplines which feature less consensus (Biglan, 1973). For engineering-based graduate students in the IDR program, engineerings' nature as a high-consensus field was particularly evident in the form of students' engineering departments' rigid (as opposed to flexible) course requirements and expectations for dissertations and relationships with advisors. Compared to their nonSTEM counterparts, engineering-based students in the IDR program were especially challenged by how scripted their engineering microsystems' expectations for graduate students' coursework, focal areas for dissertation research, as well as the expectations for the alignment of student and advisors' research pursuits were.

For example, Student AD (2023) described how they and others have been restricted and de-incentivized from pursuing activities relevant to their interdisciplinary development in reaction to their engineering disciplines' and departments' rigid and disciplinary-based expectations for PhD students' dissertation studies and coursework. They also mentioned that interdisciplinary engineering students, since engineers are often expected to conduct research associated with their advisors' work field-wide, face additional hurdles when it comes to developing interdisciplinarily when their advisor's work does not align with that development. They said,

> Requirements for dissertations and incentives definitely impact my ability to be interdisciplinary. Because with engineering, you have to, obviously, employ a certain amount of the civil engineering for your topics and your research for it to be approved to be getting a degree in civil engineering. So I think that's definitely restrictive in a way. As far as a lot of the people I know, in general, are either modeling or they're out taking data samples and not doing interviewing. It's going out on a beach and taking water samples or something. So there's definitely that staying kind of true to the field and going out and getting certain types of data, or going out and modeling certain types of things and not really incorporating social science into that. And I think there's only one person I know of who's in [the IDR program] who's doing kind of like an offshoot… And he had to fight really hard with his adviser who was supporting him to do, I want to say, more policy focused because he's interested in government… Whether that's professors maybe thinking that your research isn't up to standard, if it's not something they're used to seeing. Same with publications. You get asked about your university level, but it goes all the way to publications, to just discounting certain types of research. And I think the coursework as well, again, I didn't really have to deal with this because my adviser is very much in support of the [IDR program] coursework and me exploring different things that aren't necessarily super engineering focused.

Students AI (2023) and W (2023) corroborated, saying,

> It's like, what expertise matters in [engineering] and what should the final product look like, I think, is very rigid. And I guess incentive structures, I was just kind of thinking within my department, it might be within my discipline though. Well, kind of within my department, there's certain conferences that are more popular than others. Maybe this is kind of outside my discipline and kind of a commentary about more external things. But there's expectations about what conferences are the most important ones, as well as what journals are the most important ones in our field. And those are usually very engineering focused, not a lot of them accept interdisciplinary stuff. But I know in other departments, this happens too. There's certain conferences in certain journals that afford you, more clout, the H index is higher or whatever. And they tend to be very disciplinary-based conferences. And so there's this weird tension between getting more credit for disciplinary-type work than interdisciplinary work because of that. And the same thing seems to happen with funding. The grants that exist more-- the high-dollar grants are disciplinary based grants not interdisciplinary ones. And so it's incentivizing disciplinary work over interdisciplinary ones. And because the interdisciplinary ones are low dollar and yet interdisciplinary projects inherently require more money because it's more disciplines and more people. You end up burning people out because you don't give them enough money to actually do the work they need to do. So that's a problem that I see (Student AI 2023).
>
> Maybe it has to do partially with because engineering as a discipline is more interdisciplinary or leans more towards interdisciplinary thinking that you don't have a lot of conflict. Because I guess engineering students feel like what their discipline wants of them is constantly at odds with what an interdisciplinary program might want from them (Student W 2023).

Students AE (2022) and and AK (2023), representing the nonSTEM-based interdisciplinary graduate students in the IDR program, discussed the ways in which low-consensus disciplines' microsystems posed their own sets of issues related to the lack of rigidity or definition around expectations for PhD students. Where the engineering-based IDR students were faced with a narrowly-defined set of expectations that limited their abilities to pursue interdisciplinary work, nonSTEM-based students were challenged by their low-consensus fields' microsystems' tendencies to allow for nonSTEM students to encounter the paradox of too much freedom. The open-ended nature of their disciplines allowed for a myriad of research directions, making it challenging to define and focus on a specific research path. Adding interdisciplinary work to their loads made what already felt like a boundless set of opportunities narrow down to an even larger infinity. Student AE described this well, saying,

> One of my problems was that everything I touched seemed pretty interesting…and my advisor lets me explore whatever I want. I am not tied to her research grants with my dissertation. And it is awesome but it also feels overwhelming. There hasn't really been a research area that turns me off, and so I can't focus down on anything, because everything is pretty cool and with the interdisciplinary stuff there are even more things that I could study. I sometimes wish there was a bit more definition.

Student AE's experience points to the idea that, while nonSTEM-based students in the IDR program might have had more supportive and open advisors with more opportunities for exposure to interdisciplinary coursework and for asking interdisciplinary research questions within their departmental microsystems, they were also posed with such low consensus that many became paralyzed by the lack of a clear pathway forward and/or support structures.

The other major difference between IDR program graduate students' perceptions of microsystem dynamics across high and low consensus fields was also a similarity. Both engineering-based and nonSTEM-based interdisciplinary graduate students faced challenges with the rigidity of or lack of openness to interdisciplinarity in engineering microsystems as well as the opposing flexibility or lack of definition around interdisciplinarity in nonSTEM disciplines' and departments' microsystems. Just as Students AD, AI, and W, engineering-based IDR students cited above, struggled to take on interdisciplinary research in the face of dominant engineering academic norms incentivizing disciplinary-based work, so too did Student AJ (2023), a nonSTEM counterpart who described their interactions with an engineering faculty as such,

> The engineering professor I had last semester…I did not care for them because when they had everyone go around and introduce their research, I was the only person who they jumped on and criticized and I was also the only social scientist in the room. It felt like he needed to criticize how I used a particular word because that wasn't the way it was supposed to be used in his field. Of course, being the only social scientist, I was like, 'What is their problem? There are other definitions of resilience…" I used the word resilience or something around disasters and I felt like I was shut down. Everyone else was saying similar things, but their research was much more technical. They're using the same terms and he did not say anything to anyone, They actually told me I need to be careful when I talk. So I was not happy about that.

Additionally, just as nonSTEM-based Student AE expressed challenges with the lack of definition around their interdisciplinary work on top of already flexible expectations for scholarship in nonSTEM disciplines compared to high-consensus fields' microsystems, so too did engineering-based students like Student T (2021) discussed the challenges they faced grappling with such a wide range of research questions and methodologies explored in nonSTEM disciplines' microsystems.

> Well, at first I thought that I would like it if there were less human science courses and more technical courses. The courses outside of STEM can be a real pain because I feel like we talk about things at such a high level. At the same time, it feels like there is an endless number of ways you can spill a social research

> study compared to a technical one. And you know, just like the way I struggle to understand their research, they struggle to understand mine. And we are not always fond of each others' approaches…I had somebody tell me that there were lies, damn lies and statistics, and I was like, well, wait a second. My statistics aren't lies. Like this is data. This is – to me this is law, this is mathematical law. Some people don't see things like that and it's been really hard for me to make that leap too.

In summary, these findings underscored that challenges in interdisciplinary graduate education within the IDR program and the microsystems that make up its graduate students' mesosystems are not confined to students in high-consensus fields or solely rooted in a lack of exposure due to the rigidity of these fields' curricula. Our exploration revealed that extremism on both ends of the consensus spectrum, encompassing both high and low consensus disciplines, presents significant hurdles for the development of interdisciplinary graduate students. For those in high-consensus fields, the rigid expectations and well-defined boundaries of their departmental and disciplinary microsystems may limit the exploration of interdisciplinary avenues, constraining their ability to navigate and contribute to broader interdisciplinary conversations. For students in low-consensus disciplines, students may face the daunting task of grappling with an abundance of possibilities and the inherent ambiguity that arises from the absence of high-consensus frameworks in their disciplinary microsystems.

Conclusion

This study explored the impact of microsystems on interdisciplinary graduate students, comparing those from engineering (high-consensus disciplines) and non-STEM fields (low-consensus disciplines) within the IDR graduate program. Commonalities across disciplines included the significant influence of home disciplinary departments over the IDR program's interdisciplinary-based microsystems on students' interdisciplinary development. The study also revealed that both high and low consensus disciplines pose challenges to interdisciplinary graduate student development.

On the one hand, in high-consensus engineering microsystems, IDR students faced rigid expectations for coursework, dissertation research, and advisor relationships. The focus on disciplinary norms hindered interdisciplinary pursuits, making it challenging for students to deviate from established engineering practices. Additionally, funding and recognition structures within engineering further incentivized disciplinary work over interdisciplinary endeavors. On the other hand, low-consensus non-STEM microsystems offered flexibility but lacked clear definitions, leading to a paradoxical abundance of opportunities. IDR graduate students based in non-STEM fields found it challenging to define a specific research path amid numerous possibilities. The lack of structure and guidance within these microsystems was overwhelming, hindering students' ability to focus on interdisciplinary work.

Despite these challenges, both groups of students acknowledged the value of interdisciplinary coursework and committee members outside their disciplines. However, the burden of pursuing interdisciplinary activities fell largely on the students themselves, as program requirements are often considered additional rather than integral to their degree milestones. The lack of alignment between disciplinary and interdisciplinary microsystems affected students' motivation to engage in interdisciplinary research.

Noteworthy also was the observation that students in the IDR program, irrespective of disciplinary background, did not tend to articulate the impacts of another disciplinary department's microsystem on their development, in addition to their home engineering or non-STEM discipline and the IDR programs' microsystem itself. This tendency underscored the disciplinary-based nature of students' departmental backgrounds and the disciplinary-based nature of the IDR programs' institution where students graduate with disciplinary degrees and answer to disciplinary supervision; it also revealed how these dynamics limited the perceived significance of another discipline's microsystem in students' mesosystems. In an ideal scenario, it might be more advantageous for the academic landscape to adopt a more interdisciplinary organizational structure, wherein the mesosystems of interdisciplinary graduate students consist of multiple disciplines' microsystems. This holistic approach could foster a more enriched and diversified developmental experience, transcending the confines of singular disciplinary frameworks.

Discussion

The findings of this study contribute to ongoing discourse surrounding interdisciplinary graduate programs within the context of disciplinary-based institutions. The examination of microsystems within the Interdisciplinary Research (IDR) program, encompassing students from both engineering (high-consensus discipline) and non-STEM fields (low-consensus discipline), provides valuable insights that resonate with existing literature. For example, Newsander and Borrego [19] underscored the challenges associated with implementing interdisciplinary programs within disciplinary-based institutions. Their assertion that existing organizational cultures and structures wield influence over the generation of knowledge aligns with the observations in this study. Despite the IDR program's intent to foster interdisciplinary research, the disciplinary-based nature of IDR program graduate students' home departments and incentive and degree milestone structures impeded their ability to engage seamlessly in interdisciplinary endeavors. Our study concurs with Newsander and Borrego's finding that introducing a new interdisciplinary program without considering the existing disciplinary-based structures and cultures within an institution effectively, does not necessarily overcome entrenched university expectations favoring discipline-based scholarship.

Drawing from the study's outcomes, it also became evident that the difficulties associated with interdisciplinary research extend beyond that of engineering-based graduate students' challenges with interdisciplinary work. Contrary to the prevailing assumption, non-STEM students in the IDR program faced significant challenges to pursuing interdisciplinarity as well. Lindvig's [8] exploration of interdisciplinary PhD students in Denmark highlighted the rigidity within high-consensus fields, emphasizing constraints in defining a PhD and a PhD student. This aligns with the struggles identified among engineering-based IDR students in this study. However, our study contributed a novel perspective by shedding light on the challenges faced by non-STEM students in low-consensus fields. Specifically, the concept of the "implied PhD" put forth by Lindvig resonated with the experiences of both engineering and non-STEM students in the IDR program. The limitations on improvisation and experimentation with interdisciplinarity impacted students from both tightly defined and open-ended domains, illuminating the struggle of non-STEM students, despite the seemingly liberating nature of their disciplines, who can grapple with the overwhelming freedom and lack of defined pathways for interdisciplinary research.

In conclusion, this study echoed the cautionary notes of Newsander and Borrego regarding the implementation of interdisciplinary programs within disciplinary-based institutions and also extended existing literature by unraveling challenges faced not only by engineering-based students but also by their non-STEM counterparts. These nuanced and comparative insights contribute to a more comprehensive understanding of the intricacies involved in fostering interdisciplinary research within the confines of traditional academic structures.

Limitations and Suggestions for Future Research

We acknowledge several limitations that merit consideration in interpreting our study findings. First, our focus on a single interdisciplinary program (IDR) limits the generalizability of the results to other programs with distinct structures and compositions. Variations in institutional contexts, program designs, and disciplinary compositions across different interdisciplinary initiatives could yield diverse microsystem dynamics. Future research should explore multiple programs to discern patterns, differences, and commonalities, contributing to a more comprehensive understanding of the impact of microsystems on interdisciplinary graduate student development.

A second limitation pertains to the temporal homogenization of students' experiences over time. Interdisciplinary programs are dynamic entities, subject to changes in curriculum, policies, and institutional priorities. A longitudinal approach capturing the nuances of evolving microsystems over different cohorts could offer a more nuanced understanding of the temporal dynamics within interdisciplinary education. This approach would facilitate a deeper exploration of how programmatic changes over time influence students' experiences and interdisciplinary engagement. Moreover, the study's categorization of students into broad disciplines—engineering and non-STEM—may oversimplify the diverse nature of these fields. Within each category, students from different disciplines may face unique challenges and opportunities that shape their interactions with microsystems. Future research could adopt a more granular approach, exploring the experiences of students within specific disciplines to unravel discipline-specific nuances in microsystem dynamics.

Moving forward, a more expansive investigation encompassing diverse institutional settings could enhance the external validity of the findings. Investigating how different universities, with distinct organizational cultures and policies, influence interdisciplinary graduate education could offer insights into the role of institutional context in shaping microsystems. Future research could also consider incorporating faculty perspectives, providing a more holistic understanding of how interdisciplinary expectations are navigated and enacted within academic departments.

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