Finding Common Ground: Comparing Engineering and Design Graduate Students' Conceptualizations of Interdisciplinary Education Across Two Institutions

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Abstract

For decades, scientific and academic organizations have called for engineering graduate students who are capable of addressing complex and seemingly intractable problems in an interdisciplinary manner [1], [2], [3], [4], [5]. Several educational researchers across the globe [6], [7], [8] have sought to distinguish terms such as multidisciplinary, interdisciplinary, transdisciplinary, and recently, their convergence. However, in practice, distinctions between these terms are often fuzzy. Across academic disciplines, institutions, and geographies, terms like interdisciplinary are often understood and used interchangeably.

Even though interdisciplinary education is increasingly practiced across different academic levels and extensive research has examined its benefits, little is known about how students perceive such efforts, and this gap is especially salient in the context of graduate education, even as this context is a primary focus. Additionally, while definitions of interdisciplinarity and interdisciplinary education depend on disciplinary cultures and academic institutions [9], [10], we know little about how graduate students' perceptions of these terms might differ across institutions globally. This lack of coherent conceptual definitions can hinder educators' abilities to design relevant strategies for cultivating a global interdisciplinary workforce capable of addressing complex challenges worldwide. Thus, this study explored engineering graduate students' conceptualizations of interdisciplinary education at two international study sites – one located in Finland and one located in the United States– since previous comparative research has primarily focused on disciplinary and institutional comparisons rather than global ones. These two countries were also selected because of known cultural and pedagogical differences between their approaches to interdisciplinary engineering education.

Our dataset included 21 semi-structured interviews with graduate students, focusing on their conceptualizations and expectations of interdisciplinary education. Interviews were conducted separately at these two institutions. There were seven engineering and design graduate students from Finland and fourteen engineering graduate students from the U.S. Analysis was conducted through a comparative thematic analysis [11], focusing on the perspectives of Finnish versus U.S. graduate interdisciplinary engineering and design students.

The findings of this study shed light on similarities and differences among engineering and design graduate students' conceptualizations of interdisciplinary education. By gaining these insights into these conceptualizations, we inform international engineering educators seeking to provide support for interdisciplinary graduate students across global contexts. Furthermore, our broadened understanding of students' perspectives supports the need for a conceptual and terminological alignment in the interdisciplinary education research field.

Introduction

In the context of engineering and design education, the call for graduates capable of navigating the intricate challenges of the 21st century through interdisciplinary approaches has been persistent at both national and international levels [1], [2], [3], [4], [5]. Despite an extensive body of research on interdisciplinary education, a crucial gap remains in understanding how graduate students– specifically those in engineering and design that both strongly benefit from interdisciplinarity– conceptualize interdisciplinary education. Researchers have explored the constructive alignment of learning outcomes and experiences in interdisciplinary graduate education [12], [13], [14] and how to evaluate interdisciplinary graduate programs and student development in light of their complexity [9], [15], [16], [17], [18]. At the same time, scholars have sought to define terms related to interdisciplinary learning, delving into terminological nuances and seeking conceptual convergence and shared meanings [8], [10], [19], [20], [21], [22], [23], [24]. Yet, in practical applications (including both program names and daily conversation), the distinctions between terms such as multidisciplinary, interdisciplinary, and transdisciplinary remain ambiguous and the terms are often used interchangeably. The lack of precision in these definitions is further compounded by the influence of disciplinary cultures and institutional contexts, which can make it challenging to cultivate a shared language and shared meanings for a global, adaptable interdisciplinary workforce of engineers and designers [7], [9], [10].

In scoping this study, we first operationalize three widely distinguished terms in the existing literature – multidisciplinary, interdisciplinary, and transdisciplinary learning. Current scholarship use "multidisciplinary" to characterize learning that involves exposing students to multiple academic disciplines, working in parallel under a common thematic umbrella, with each discipline maintaining its own goals. In contrast, researchers use "interdisciplinary" to describe learning that crosses disciplinary boundaries to develop integrated knowledge through synthesis and a common language. Finally, "transdisciplinary" refers to learning that moves beyond individual academic disciplines to engage in co-production of knowledge and methods, often involving non-academic stakeholders [20][21][22][23][24]. The multi-, inter-, trans- prefixes for these kinds of learning capture the increasing levels of integration of knowledge and the related interactions.

But despite growing consensus at the scholarly level, in practice programs that describe themselves as "interdisciplinary" (perhaps the most common term) do not necessarily rigidly adhere to scholarly conceptions. To that end, our research seeks to understand how graduate students participating in programs that define themselves as "interdisciplinary" (in their titles, descriptions, and/or goals) understand what interdisciplinary learning means.

The focus on students' understanding of interdisciplinary learning is the key novelty of our study, as prior engineering education research on interdisciplinary education has predominantly centered on faculty perspectives when exploring academics' conceptualizations of interdisciplinarity. For example, Feng & Hölttä-Otto's [22] study focuses on faculty members' conceptualizations and course design considerations of multi- and interdisciplinary learning in engineering education, and Lattuca & Knight's [10] study examines faculty and administrators' perspectives alone. These studies offer valuable insights into the significance of academics'

perspectives on interdisciplinary learning. However, the focus on faculty and administrators within single institutions can mask a broader set of diverse conceptualizations, as well as commonalities, across the educational ecosystem. In addition, studies on students' experiences in graduate programs stress that interdisciplinary graduate students often struggle to develop positive senses of identity, belonging, and motivation necessary for pursuing interdisciplinary work as early-career academics [25], [26], [27]. They are challenged to understand and integrate discipline-based expectations of Ph.D.s [15] and to find and sustain the kinds of collaborative interdisciplinary experiences necessary for their persistence in interdisciplinary engineering and design careers, often with little support [9], [17], [26], [28], [29]. These barriers suggest that we need to develop more robust understandings first of how students conceptualize interdisciplinary work, which in turn can help inform approaches to enhancing programs and curricula.

In this context, we argue that it is particularly important to conduct comparative international research to better understand how conceptualizations of interdisciplinary education are not only discipline-dependent but also culturally and institutionally contingent. Such a comparative study can help inform curricular design to foster students' understanding of global competence. As a first step in such efforts, we used reflexive thematic analysis within a comparative case study [11], [30], [31] to identify interdisciplinary graduate students' conceptualizations of interdisciplinary education at two universities, one in Finland and one the U.S. The research question(s) associated with this work are the following:

RQ 1. How do graduate engineering and design students commonly conceptualize interdisciplinary education across two universities?

RQ 2. What are the variations in students' conceptualizations of interdisciplinary education across the two universities?

Methods

Study Background

Study Site 1: A United States University

Our first project site was an interdisciplinary graduate program (referred to as the IDR Program from here) funded through the National Science Foundation (NSF) Research Traineeship program at a large land-grant university in the mid-Atlantic region of the United States. As the NSF website states, "The NSF Research Traineeship (NRT) Program is designed to encourage the development and implementation of bold, new potentially transformative models for STEM graduate education training." Some of the purposes of the IDR graduate certificate program were to provide interdisciplinary graduate students with intentional training in integrating social context into their disaster resilience research as well as facilitating students' interdisciplinary development by engaging IDR faculty and graduate students in a community of practice. The program, centered on disaster resilience, was designed to spur convergent research collaborations as well as interdisciplinary skill development in resilience for both graduate students (masters and Ph.D.) and faculty in STEM, business, policy, governance, natural resources, and humanities. IDR offered courses to graduate students across levels and disciplines, funding for

doctoral students completing the program's certificate, and opportunities for both students and faculty to build interdisciplinary collaborations inside and outside their university. Twelve credit hours of classes, along with interdisciplinary workshops and other events, provided student researchers opportunities for overcoming discipline-specific conceptualizations of disasters, generating interdisciplinary knowledge for achieving resilience, and developing their professional identities as interdisciplinary researchers. To date, the IDR program has graduated just under 40 students.

Study Site 2: A Finnish University

The second project site was a university in Finland, where interdisciplinarity is part of the core university strategy for education and research. Following its establishment, this Finnish University embraced a forward-looking mission to integrate science, art, technology, and business. To operationalize the mission, the university has been initiating and implementing a wide range of interdisciplinary educational courses and programs. These initiatives span across different academic levels, including both master's and bachelors. At the course level, there are pioneering initiates with a strong career-relevant emphasis, such as Product Development Project and Sustainability Global Technologies, designed to foster both practical and theoretical skills for interdisciplinary problem-solving and knowledge co-creation. On the program level, there are major and minor degree programs, such as International Design Business Management, and Creative Sustainability, a minor program in product development, tailored for undergraduate students. For the studied programs, we collected data from student participants in four Master's programs. These programs are interdisciplinary, with a focus on either engineering or design, thus we had a diverse group of student participants from both fields.

Data Collection and Participants

Study Site 1: A United States University

This study used secondary semi-structured interview data that was collected as part of the National Science Foundation NRT Grant supporting the IDR program. Each year of the IDR Program's NRT Grant (5 years in total from 2019 to 2023), participating interdisciplinary graduate students were interviewed for mandatory grant program assessment purposes. These interviews primarily focused on graduate student experiences in their interdisciplinary program and what pupils found to be helpful or challenging about their academic environments and the development of interdisciplinary identities. The specific research at hand centers on students' responses to key questions that delve into the core concepts of interdisciplinarity. These questions include:

- How do you define "interdisciplinarity"?
- How do you define "interdisciplinary research"?
- How do you define "interdisciplinary scholar"?

The dataset for this specific study comprised 14 one-hour interviews conducted with interdisciplinary engineering graduate students participating in the IDR program during their inaugural year in the program. The intention behind selecting this particular time frame was to

capture the early conceptions of interdisciplinary learning and education among graduate students embarking on their IDR journey. It is important to note that though the IDR program granted interdisciplinary graduate certificates, most researchers involved in IDR were still housed within disciplinary departments, managing disciplinary-based expectations of scholars and earning formal disciplinary degrees. These interdisciplinary engineering students were specifically spanning engineering disciplines including civil engineering (CEE), engineering education (ENGE), industrial and systems engineering (ISE), as well as biosystems engineering (BSE) departments. Recruitment was not a focus of garnering this interview dataset, as participants' interviews were initially gathered as part of a mandatory grant program assessment and general interdisciplinary graduate education research purposes. Specifically, all funded IDR graduate students were invited to participate in interviews for program assessment and subsequently asked if they would allow their data to be used for research. As such, this dataset relied on a convenience sample, drawn from an existing pool of participants. All participants were assigned pseudonyms for participants de-identification.

Study Site 2: A Finnish University

This study uses a subset of secondary data drawn from a larger research study at the same Finnish University, which investigates students' conceptualizations of and experiences in interdisciplinary education. Specifically, the dataset consists of seven semi-structured interviews conducted with graduate students during their first year. These interviews form part of a longitudinal study, with follow-up interviews planned to track changes in students' conceptualizations, experiences, and learning gains over time.

The semi-structured nature of the interviews was designed to provide ample opportunity for students to share their prior experiences, expectations of their interdisciplinary studies, and their current experiences in the program. The questions during the interviews were intentionally broad and exploratory, to elicit interesting and important patterns and build the foundation for future interviews. Key questions included:

- Why did you choose to enroll in an interdisciplinary graduate program?
- What were your expectations for interdisciplinary studies?
- How do you perceive working with peers from different disciplines?
- Can you discuss any courses that combine multiple disciplines, and how do they do so?
- In what ways do you think learning from other disciplines will influence your future career?
- How do you collaborate with other teammates on projects?
- What have you learned from this program so far, and what challenges have you encountered?

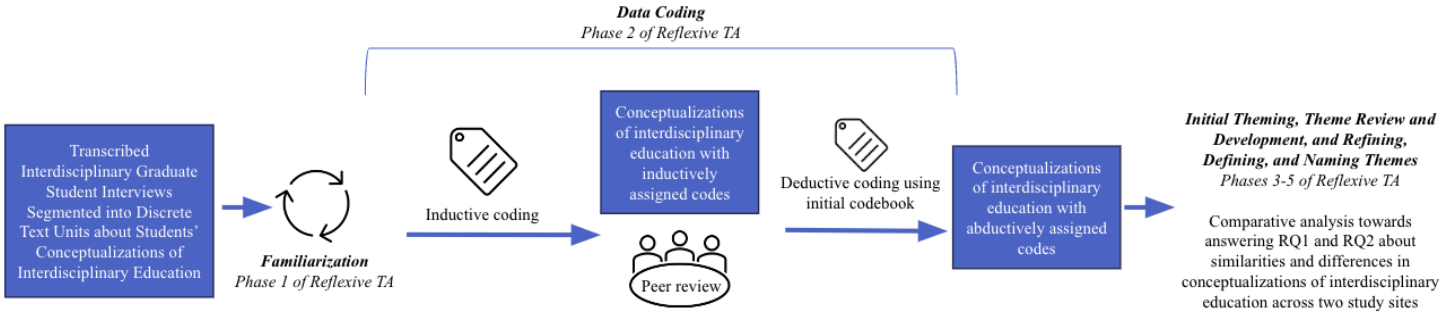
The dataset for the current study consists of interviews with seven participants. Among these, four enrolled in design-oriented interdisciplinary programs, and three in engineering-oriented programs. All participants were assigned pseudonyms for participants de-identification.

Reflexive Thematic Analysis

Study Site 1: A United States University

Once the interviews from our first project site were transcribed, two members of our research team began analyzing the data via Reflexive Thematic Analysis (TA) [11], [32], [33], [34], [35], 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.* An overview of these methods is depicted in Figure 1.

Figure 1: Overview of Our Reflexive Thematic Analysis and Comparative Approach



During data familiarization (TA Phase 1), we first separated participants' responses to the specific interview questions being focused on in this study into discrete units of text. Independently, we immersed ourselves in these text units, employing recursive reading to grasp the nuances of students' perspectives on interdisciplinary learning and education. Throughout this process, we maintained memoing to document evolving insights. Subsequently, we discussed our work, pooling our understandings derived from the initial readings. This collective dialogue laid the groundwork for the second phase of our analysis, which involved coding.

After achieving a comprehensive understanding of students' definitions of interdisciplinarity, we established a shared sense of the dataset. Following this consensus, we embarked on an independent coding process (TA Phase 2). Employing an inductive approach, we delineated codes without a pre-existing framework, often utilizing in-vivo codes to encapsulate students' expressions in their own words. To ensure consistency and reliability, we compared our separate coding endeavors, leading to the creation of an initial codebook.

This initial codebook became the basis for a subsequent deductive round of coding. In this phase, we aligned our codes with our pre-established framework. Throughout this process, we underscored the abductive nature of our analytical efforts — the endeavor to draw the most plausible and nuanced conclusions based on our dataset. The cyclic interplay between inductive and deductive methodologies enriched our analysis, fostering a thorough exploration of students' conceptualizations of interdisciplinary learning and education.

At the end of these recursive phases, we were then able to start theming (TA Phase 3), which involved identifying and organizing recurring patterns, concepts, and meanings within the coded data. We systematically examined our coded segments to uncover overarching themes that encapsulated the essence of the students' perspectives on interdisciplinary learning and education. At this point in the analysis, we had our initial codebook for our U.S.-based site's dataset applied to Project Site 1's interviews. Phases 4 and 5 of TA in this study then involved comparing this U.S. codebook with that of its Finnish counterpart (methods for this are described next) to review and develop both common and unique themes, refine, name, and define them appropriately, as well as begin answering our research questions.

Study Site 2: A Finnish University

To uncover the commonalities and variances of students' conceptualizations across two distinctive institutions, the analysis in Project Site 2 began by leveraging the codebook developed at Project Site 1. This involved utilizing the pre-established coding framework as a baseline. Subsequently, the Finland-based analysis team employed abductive coding to address aspects of the data that were not adequately captured by the existing framework, which led to necessary adjustments and enhancements to the coding methodology.

During data familiarization (TA Phase 1), one of the Finland-based team members reviewed all the transcripts. The review included identifying interesting patterns and assessing the alignment between the Finnish study site's data and the coding framework established by the U.S.-based team. Insights gained from this phase informed the adjustment of the coding framework and the subsequent coding procedures. In the next phase (TA Phase 2), three Finland-based team members applied a deductive approach to begin coding the data, guided by the refined framework. This phase focused on identifying preliminary themes and categories.

Then, the Finland-based team progressed to initial theming (TA Phase 3). During this phase, the Finland team systematically organized the key findings, aligning them with the structure of the coding framework. We also coded the key findings that do not align with the framework. In the theme review and development (TA Phase 4), we reviewed our codes and emergent categories.

During the final coding phase (TA Phase 5), the team engaged in inductive coding to address the findings that did not conform to the existing framework. This has led to the development of the integration of new codes into the framework, enhancing its comprehensiveness.

Comparative Thematic Analysis Methods

Following this, both the Finnish and U.S.-based teams engaged in collaborative discussions about the shared and unshared aspects of each of their coding frameworks. These discussions were essential in further refining the frameworks and ensuring the robustness and validity to accommodate both datasets effectively. Finally, with a final and refined framework in place, we transitioned to writing the results. This stage involved synthesizing the findings from the analysis into coherent and well-structured categories and sub-categories of themes.

Limitations

While the findings of this study offer valuable insights into graduate students' conceptualizations of interdisciplinary education, several limitations impact the interpretation and transferability of the results. First, this study does not claim causality between the observed conceptualizations and any specific factors or interventions. The qualitative nature of the research design allows for the exploration of graduate students' perspectives on interdisciplinary education, but it does not establish causal relationships between variables. Future research employing longitudinal or experimental designs could provide more robust evidence regarding the effects of interdisciplinary education programs on students' conceptualizations and experiences.

Second, the data analyzed in this study were collected from two datasets that were not explicitly designed to answer the research questions, which limited the depth of insight and the ability to probe further into specific nuances of graduate students' conceptualizations. That is, because explore students' conceptualization of interdisciplinarity and interdisciplinarity was not the goal of the interview, interviews did not necessarily probe participants' responses for clarifications and expansions. As a result, the data may not fully capture all nuances how participants define interdisciplinary work and learning. Additionally, the datasets from both institutions were small, potentially affecting the generalizability of our findings. To counter this, we conducted a qualitative and in-depth analysis to reveal detailed and transferable insights into each institution's contexts and dynamics.

Third, although this study does compare data from institutions in two different countries, and thus offers some global context, neither institution is treated as representative of all institutions in its home country, nor were the specific programs selected as representative of programs within each institution. Instead, these exploratory results are designed to illuminate both shared meanings (including alignment with scholarly definitions) and differences that can impact where, how, and to what extent graduate scholars continue to pursue interdisciplinary work.

Fourth, participants located in both Finland and the U.S. had diverse academic backgrounds, with Master's students in Finland and both Master's and Ph.D. students in the U.S. This difference might impact students' inclination towards interdisciplinary research. Future work might address this in more detail by aiming for a nuanced understanding of how graduate students engage with interdisciplinary work across not just different institutions but also academic levels.

Finally, interdisciplinary education encompasses a broader scope than the conceptualizations and themes presented in this study. While this study focused on graduate students' conceptualizations of interdisciplinary learning outcomes, practice, impact-making, and identity reconstruction, interdisciplinary education also encompasses other activities such as curriculum design, institutional policies, and interdisciplinary research collaborations that can vary widely across contexts. Future studies could explore these additional dimensions to provide a more comprehensive understanding of the different aspects of interdisciplinary education.

Findings

RQ 1: How do graduate engineering and design students commonly conceptualize interdisciplinary education across two universities?

Our results indicate that graduate students from the U.S. and Finland institutions conceptualized interdisciplinary education through various themes, with some of the themes strongly prevalent in both contexts and some only on one of them. Yet, the recognised themes can be generally grouped into four key categories that all are visible in both contexts: interdisciplinary learning, interdisciplinary practice, impact-making, and identity (re)construction. While there are nuances in how students described these aspects, they all emphasized learning knowledge, 'languages' (specific terms and communication cultures), and methods of other disciplines, collaborating with others, making an impact on the public, adopting a new mindset, and applying interdisciplinarity in practice in various ways (Table 1).

Table 1: Key Themes in Graduate Students' Conceptualizations of Interdisciplinary Education and Percentage of Students' Who Mentioned These Themes across Two Sites

Category	Preliminary Themes	US % of students mentioned	Finland % students mentioned
Interdisciplinary Learning Outcomes	Collaborating across and integrating disciplines	86%	100%
	Gaining disciplinary knowledge from others	86%	100%
	Learning the 'languages' and methods of other disciplines	71%	57%
Interdisciplinary Practice	Extending one's work to apply in other disciplines	29%	29%
	Bringing other disciplines in to receive feedback	36%	42%
	Working in an emergent space to combine insights	64%	42%
	Expanding own toolbox to engage with other disciplines	43%	0%
	Developing interdisciplinary language and communication skills	50%	0%
Impact-making from Interdisciplinary Education	Recognition as an interdisciplinary researcher by significant others and institutions (i.e., journals, funding agencies)	64%	0%
	Contributing to the public through one's interdisciplinary work	50%	42%
	Improving individual abilities to do interdisciplinary work	0%	86%
	Improving collective abilities to do interdisciplinary work	0%	57%
Identity (Re)-construction and Shifts in Mindset	Developing an identity as an interdisciplinary researcher	7%	0%
	Widening own disciplinary identity	0%	29%
	Maintaining one's own disciplinary identities while venturing into other disciplinary domains	0%	42%
	Adopting new lenses, values, or mindsets with which to view disciplines and interdisciplinary work	29%	86%
	Developing confidence and comfort in other disciplines	36%	0%

Note. The color gradient from light to dark blue in Table 1 represents relative percentages from low (0%) to high (100%) of students at each study site who mentioned the given theme. The differences in the relative percentages between the two study sites might be partly due to differing questions (see Methods section).

Interdisciplinary Learning Outcomes

Both the U.S.-based and Finland-based graduate students' most commonly cited conceptualizations of interdisciplinary education were related to describing the specific learning outcomes. Students described these primary learning outcomes as developing their abilities to collaborate across and integrate disciplines, gaining disciplinary knowledge from others, and learning the 'languages' and methods of other disciplines. For example, at the U.S. site, Grace said "To me, [interdisciplinary education] is about learning to conduct research with researchers from several disciplines… to collaborate with researchers spanning multiple different disciplines".

Similarly, Finland-based students highlighted the importance of integrating and collaborating across disciplines. Particularly in course projects, they highlighted learning to collaborate with peers from different disciplinary backgrounds and to combine knowledge from various fields, such as design and business, or physics, engineering, and mathematics. For example, Alex shared the experience of working with business and engineering students and how important it is to "adapt to each other's positives and negatives and pull out the best from each other".

Both U.S.-based and Finland-based students also emphasized learning from other disciplines. To describe what it meant to gain disciplinary knowledge from others, Mei (US) shared that:

> Becoming an interdisciplinary scholar involves gaining knowledge about multiple disciplines... An interdisciplinary researcher is someone who has expertise in multiple disciplines and can use that expertise to improve each of the disciplines in some way, shape, or form.

At the Finland site, all seven students emphasized the acquisition of disciplinary knowledge. This involved gaining new knowledge from one or more disciplines. Particularly, the engineering and design students learned from fields, such as marketing and sustainability. For instance, as an engineering student, Thomas discussed learning from a business peer who "had really good ideas on … creating business cases … and the commercial aspect of their solution, and that refined their case very well".

Students at both sites also discussed seeing interdisciplinary education as learning the 'languages' (specific terms, jargon and communication cultures) as well as methods of other disciplines, mentioning things such as

> In this program, I have had the opportunity to work with other disciplines, and I find that we speak different languages. And it's really hard to work with other disciplines if you don't have previous experience or you don't know how to do it. So, by joining this group, I think I can obtain those uh abilities...to speak different languages across disciplines. - Juan (US)

> [As designers], we are used to talking about design work, but engineers are not used to doing that. As for business people, they are [speaking] in a very strategic way … so I need to facilitate a lot of things. - Alex (Finland)

In summary, these conceptualizations of interdisciplinary education in terms of learning outcomes identified among both the U.S.-based and Finland-based graduate students revolved around the development of collaboration skills, gaining knowledge from various disciplines, and

acquiring the ability to navigate the 'languages' and methods of diverse fields. These outcomes underscored the importance of collaborative experiences and the acquisition of interdisciplinary expertise for fostering growth as researchers.

Interdisciplinary Practice

The second most cited conceptualization of interdisciplinary education for both sites' students was related to students' views of the working practices of interdisciplinary work and the things they are doing as developing interdisciplinary researchers towards meeting their learning outcomes. Specifically, students from both institutions viewed interdisciplinary practices as (1) extending one's work to apply in other disciplines, (2) bringing other disciplines in to receive feedback, (3) working in an emergent space to combine insights.

In particular, three Finland-based students recognized the significance of bringing other disciplines to receive feedback. David and Kelly, for example, highlighted the benefits of bringing a design mindset to enrich engineering problem-solving, and Mark discussed the critical role of marketing in the product development process. U.S.-based student Olivia described this theme as

> I think [with interdisciplinary education] I'm most interested in working on problems in my field in areas where I have the most expertise. I want to push my field forward, but I recognize that there are ways that I can push forward my field while stepping, again, just slightly adjacent to or slightly outside of my research focus and getting advice and knowledge from other related disciplines. So if there are research questions to be answered there, and even though they're slightly outside of my area of expertise, then yeah, I want to be able to step outside of my expertise and try to understand those problems as related to and able to inform my work.

In addition to incorporating perspectives from other disciplines, one Finland-based student discussed extending their disciplinary expertise to contribute to different fields. For example, Ella, with their engineering foundation, highlighted the need to apply their technical expertise to address problems in other areas, such as sustainability. U.S.-based students Jamal and Ricard echoed these sentiments, saying that

> Interdisciplinary education involves becoming a researcher who contextualizes their work beyond their ontologies, epistemologies, and theoretical frames. In a way that it not only includes but empowers researchers from other backgrounds to engage with their work. (Jamal)

> In my [interdisciplinary education] I want to be able to understand folks across disciplines as well as help them understand what I do. I think there's a lot of value in being able to do that because it's like crossing borders. It's like being in my own country… if I can take what I have and share it with others and take what others have and bring it to whatever I have. It's just a cooler way of doing things. (Ricardo)

The concept of working in an emergent, interdisciplinary space, was another common theme among three Finland-based students. David, Mark, and Kelly advocated for the fusion of design, business, and management principles. They perceived this integrative approach as essential for achieving a holistic perspective in problem-solving and fostering creativity. U.S.-based students Mei and Ricardo, respectively, described this conceptualization of interdisciplinary education as

“it connects with research just using different disciplines to kind of solve one huge problem” and "it is when there are different teams of different disciplines working together to investigate the same problem that cannot be solved by one discipline by itself.”

Impact-making from Interdisciplinary Education

Both U.S.-based and Finland-based students highlighted the importance of making an impact through interdisciplinary education. Specifically, students emphasized contributing to the public through one’s interdisciplinary work.

For example, those graduate students located in the U.S. who were more focused on the public impacts of their interdisciplinary research said things along the lines of, “Getting an interdisciplinary education is not only about publishing, but also having some impact on the community” (Emily), “because I feel like in the future, or even now… everything becoming interdisciplinary… there are so many different things that affect everybody… But it affects everybody in different ways, so understanding how different people are affected by the same thing is critical” (Mei). Similarly, at the Finnish study site, three students expressed their intentions to have a significant societal impact by addressing complex issues. In particular, environmental sustainability was the most frequently mentioned challenge that these students were keen to tackle. For example, Kelly discussed achieving “sustainability entrepreneurship requires interdisciplinary knowledge to break free from a money-based system”.

Overall, these insights imply that graduate students at both institutions perceive interdisciplinary education as a pathway to personal and academic growth as well as a means of making meaningful contributions and being acknowledged on a broader scale within and beyond their academic communities.

Identity (Re)-construction and Shifts in Mindset

Both sites’ students discussed the processes of identity reconstruction and shifts in their mindsets pursuing interdisciplinary work and research. Particularly, they emphasized how their personal and professional identities have evolved and re-shaped through exposure to other fields. Students have shared how they have adopted a new lens, mindset, or set of values. For example, at the U.S. site, Emily explained:

> [Interdisciplinary education] involves [a shift of] mindset to listen to other disciplines’ research. it’s not important about the level of understanding... but it is more to work with other people than like you understand the – nuts and bolts of what they're doing. If people have the mindset of trying to listen to others then understanding will follow naturally.

Grace (US) also provided insight, stating,

> An interdisciplinary scholar [is] somebody who wants to span disciplines … and values interdisciplinary research approaches.

At the Finland site, all students discussed the long-term transformation of their views on disciplines and interdisciplinary fields. Kelly, for example, discussed evolving from viewing

design through the lens of graphics to appreciating its broader applicability, such as in the business field for ideation processes like convergent and divergent thinking.

RQ2: What are the variations in graduate students' conceptualizations of interdisciplinary education across two universities?

Graduate engineering and design students at both sites conceptualized interdisciplinary education through the four key categories of themes– interdisciplinary learning, interdisciplinary practice, impact-making, and identity (re)construction (Table 1). Out of the four categories, there were no notable differences between the two institutions on the students' descriptions of interdisciplinary learning outcomes., Yet, all remaining categories had interesting differences that are discussed next in detail.

Impact-making

The differences in conceptualizations of interdisciplinary education between our two study sites were most emphasized in how the students saw impact-making from interdisciplinary education.

At the Finnish site, students saw interdisciplinary work as having an impact on their abilities to do interdisciplinary work, with a specific focus on individual and collective capabilities of problem-solving. They suggested that by exploring different fields to become versatile talents and grow more capable of integrated thinking and maximizing the effectiveness of their efforts. Specifically, Emily and David highlighted the importance of expertise in business, technology, and design for more efficient problem-solving and project management, as opposed to relying on a single-discipline approach. That said, these students based in Finland also acknowledged the potential of collective endeavors, where the sum of individual contributions often triumphs in isolated endeavors. Ella pointed out that "relying solely on one's specialization might miss out on important details", and it is important to have "different kinds of knowledge".

In contrast to the Finnish site's additional themes related to interdisciplinary education as improving individual abilities to do interdisciplinary work, U.S.-based students' conceptualizations of impact-making in interdisciplinary education that Finland-based students did not mention included recognition by significant others and institutions (i.e., journals, funding agencies) both within and outside a home discipline as an interdisciplinary researcher. In particular, graduate students in the U.S. site saw interdisciplinary education as involving gaining recognition by significant others outside one's home discipline as an interdisciplinary researcher, sharing that:

> Yeah, I think the goal of [interdisciplinary education] is being acknowledged by other disciplines… If I was only acknowledged within my field, I wouldn't think that I was an interdisciplinary scholar. But to know that other fields can acknowledge me, and we can even have conversations of, 'Oh yeah, I can, and this is what another student within disaster resilience and risk management and was like, oh we should work together. Like I see a lot of stuff that I'm doing that you're doing. And how that aligns.' (Sophie)

Overall, these insights suggest that graduate students at the U.S. study site perceived interdisciplinary education as a pathway to personal and academic growth as well as a means of

making meaningful contributions and being acknowledged on a broader scale within and beyond their academic communities.

Identity reconstruction

Both study sites' (US and Finland) students' descriptions differed on the ways of (re)constructing one's identity and shifts in mindset. The U.S.-based students highlighted developing confidence and comfort in other disciplines and developing an identity as an interdisciplinary researcher. For students based in Finland, they focused on maintaining their own disciplinary identities while venturing into other disciplinary domains. For example, Thomas said, "I did not want to let go of my engineering [identity] but also would like to focus more on management and strategy". Ella also adopted a similar approach, sharing that "it's crucial to have a foundation and expand into different fields, such as sustainability".

Finland-based students also reshaped their identity by widening their disciplinary identity. Specifically, two students spoke about exploring a wider range of career possibilities. For example, Emily recounted her initial view of perceiving an engineer as someone working behind computers. Now, her perception of engineering has expanded to include integration with project and team management. Similarly, Alex talked about developing a more generalist identity, enabling the exploration of diverse career paths, such as entrepreneurship, research, or design. Alex also shared going beyond to work as a designer to give critical feedback to others and become a facilitator in brainstorming and organizing review sessions with other team members.

US-based students highlighted that the development of confidence and comfort in engaging with other disciplines was a significant aspect of these students' shifts in mindset as a result of pursuing interdisciplinary education. Emily reflected on this, stating, "So if you were to describe yourself as an interdisciplinary scholar, then you would be comfortable working with other disciplines". Additionally, one U.S.-based student expressed the shift in self-identification as an interdisciplinary researcher through working across bodies of knowledge. Ricardo mentioned,

> Interdisciplinary education is working across bodies of knowledge. Becoming interdisciplinary... I think it's how we identify ourselves. So even though I identify as an engineer I don't necessarily identify as a civil engineer only. Like I feel like I know nothing about – very limited knowledge about civil engineering... I'm more in between disciplines. So I think it's almost how we identify ourselves and for me, I don't identify as a civil engineer in any way or as a social scientist alone. I am interdisciplinary. And for me, that's different.

These unique findings from graduate students located in the U.S. illustrate the intricate interplay between academic identity and mindset shifts as students engage in and conceptualize interdisciplinary education, as well as the recognition that interdisciplinary engagement involves embracing diverse points of view.

Interdisciplinary practice

While both the U.S. and Finland study sites' students' ways of describing interdisciplinary practice were similar, the U.S.-based students' descriptions were more diverse. Students converged in describing interdisciplinary practices as working in an emergent space to combine

insights, bringing other disciplines in to receive feedback, and extending one's work to apply in other disciplines. Only the U.S.-based students discussed expanding their toolbox to engage with other disciplines and developing interdisciplinary language and communication skills.

One U.S.-based student quote illustrating the theme of 'expanding their toolbox' came from Juan who said, "Interdisciplinary education involves learning different points of view, and developing different toolkits so you can work together."

Discussion, Conclusions, and Future Work

Our study aimed to uncover the conceptualizations of interdisciplinary education held by graduates studying in two different educational contexts: one university in the United States, and another in Finland. Through a detailed analysis of conceptualizations of interdisciplinary education, several themes emerged across both secondary datasets that could be grouped into four key categories of themes: interdisciplinary learning outcomes, interdisciplinary practice, impact-making, and identity (re)construction. Graduate students from both institutions articulated a shared understanding of interdisciplinary education, emphasizing the importance of collaboration, gaining knowledge from diverse disciplines, and learning the languages and methods of other fields. These conceptualizations reflect key learning outcomes proposed for interdisciplinary education. Borrego and Newswander [8] outline key learning outcomes for interdisciplinary graduate programs, including grounding in multiple traditional disciplines, integration skills, teamwork, interdisciplinary communication, and critical awareness. Our findings resonate with these outcomes, as graduate students from both the U.S. and Finnish institutions emphasized the importance of collaborating across disciplines, gaining knowledge from diverse fields, and developing interdisciplinary communication skills.

However, it is noteworthy that while the categories of themes identified in our study align with these outcomes, there exist nuances in how graduate students perceive and prioritize them within their educational experiences. In particular, while there were commonalities in how students from both the U.S. and Finland conceptualized interdisciplinary learning, there were notable variations around impact-making, identity reconstruction, and interdisciplinary practice. These variations may be attributed to internal and external factors such as institutional strategy, socio-cultural environment, and prior educational and professional experiences. In previous analyses of the U.S. site, for example, we identified factors ranging from student-advisor relationships to institutional priorities to national funding that shaped the way students engaged in the interdisciplinary program [36]. Similarly, at the Finnish study site, several studies also highlighted the impact of regional engineering education framework, institutional strategy, teachers' professional experiences, and certain course/program characteristics, and how they influence interdisciplinary course design and consequently students' conceptualizations and learning experiences [21], [37], [38]. The potential role of national educational policies and practices aligns with other recent comparative work on topics such as education for sustainable development and engineering education priorities [39], [40].

At the same time, even studies within one institution or country identify variations in scholars' perceptions and practices of interdisciplinary work. For example, Lattuca and colleagues' [41], [42], [43] treat interdisciplinarity as a spectrum ranging from exposure to true collaboration. These perspectives offer lenses through which to interpret our findings. The diverse

conceptualizations of interdisciplinary practice and impact-making across both U.S.- and Finland-based graduate students suggest varying levels of engagement with interdisciplinary collaboration. While some students highlighted the importance of integrating insights from other disciplines and working in emergent interdisciplinary spaces, others focused more on individual recognition and impact-making within their home disciplines. This variation underscores the complexity of interdisciplinary education and the need for educators to consider diverse student perspectives in program design and implementation. As an added note, scholars like Field, Lee, and Field [44] emphasize the development of humility, sensitivity to bias, and a sense of empowerment as integral aspects of interdisciplinary learning. While these themes were not explicitly articulated in our findings, they may represent additional dimensions of interdisciplinary education that warrant further exploration in future research.

In sum, our study results suggest that despite extant scholarship on interdisciplinary graduate education and the development of interdisciplinary graduate programs, there exist nuanced differences between established definitions of interdisciplinary learning outcomes and the conceptualizations of graduate students both in general and based on context. Our findings represent a misalignment between established definitions of interdisciplinary graduate education and what graduate students are expecting in their interdisciplinary learning outcomes, highlighting the need for further exploration and refinement in aligning educational goals with student expectations globally. Specifically, when considering our conceptual definition of interdisciplinary learning (i.e., crossing boundaries between disciplines to develop integrated knowledge through synthesis and a common language), the findings highlight additional aspects that graduate engineering students associate with interdisciplinary learning. These include an emphasis on collaboration, impact-making, and identity (re)construction. Although aligned with some of the proposed interdisciplinary learning outcomes, they suggest that graduate students can have expanded and differently-prioritized views of what interdisciplinary education entails beyond simply crossing boundaries and integrating knowledge. In addition, the differences between U.S.- and Finland-based graduate students' conceptualizations indicate the potential influence of institutional context on these students' views of interdisciplinary education, suggesting that localized factors may play a significant role in shaping student expectations and experiences.

Recognizing and addressing these novel perspectives to conceptualizations of interdisciplinary learning can help bridge the gap between how interdisciplinary education is formally defined and how students actually experience it. Neglecting students' nuanced perspectives could lead to a disconnect between the intended learning outcomes and the students' motivations, expectations, and perceived benefits of interdisciplinary programs. Explicitly incorporating elements like collaboration skills, impact awareness, and professional identity development into program design and delivery can enhance the relevance and effectiveness of interdisciplinary education for engineering graduates. Ultimately, aligning defined objectives with student conceptualizations is crucial for equipping the next generation of engineers with the holistic capabilities needed to tackle complex, cross-cutting challenges in their future careers and roles. In terms of addressing in more detail the divergence between students' conceptualizations across different settings, we raise questions about the influence of institutional context on graduate students' expectations and experiences. Future research could examine institutional factors in shaping students' perceptions, such as curriculum design, faculty expertise, and culture.

Additionally, longitudinal studies tracking students' experiences over time could provide insights into the longer-term impact of interdisciplinary education on their professional identities and career trajectories.

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