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Convergence Research in Graduate Engineering Education

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The National Science Foundation (NSF) and other funding agencies identify convergence as an overaching goal for academic research in science and engineering fields. While many academic researchers in the U.S. explicitly acknowledge the value of convergence, they report difficulty in creating educational programs that can prepare new generations of researchers for this goal. Building on the interviews with graduate students in engineering and related fields at Worcester Polytechnic Institute, a mid-size tech school in the U.S., this paper explores the students' experiences of 'convergence research' (CR) in an NSF-funded research training program. We present a view of CR as a set of structured flows of feedback among researchers and between researchers and others in and beyond academic institutions.

In contrast to recent scholarship on CR, we propose a framework of CR that considers the emergence of systems from such feedback flows—not vice versa. Some of these flows stabilize the process of CR inquiry, while others destabilize. The stabilizing feedback flow is crucial to producing actual impact in the world—a research output needs some kind of stability to be produced. The destabilizing feedback flow offers questions to reflect on the framing of the research problem. In doing so, it opens up a space to think outside of conventional boundaries of disciplinary science. These two types of flows are not mutually exclusive; they indeed work in tandem. The 'convergence researcher' needs to learn to navigate both, so CR is theoretically innovative, methodologically critical, and socially meaningful. We argue that the convergence

researcher needs to be trained to have the preparedness to think of the research process through the lens of feedback flows. In this paper, our main focus will be on destabilizing feedback, as it became a prominent theme in our interviews with the graduate student researchers.

Looking at CR from the perspective of feedback helps build a framework that centers the experience of the 'convergence researcher' (instead of the output of convergence research). In prioritizing the experiential dimension, our account draws attention to the fact that it is the researchers and their relations that make CR possible. We believe that this adjusted framework can be helpful to graduate student research training programs in general.

Convergence in Education

The National Research Council's 2014 report—*Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond*—notes that "significant efforts have been made over the past decade to revise STEM education…with particular emphasis on prompting training that makes interdisciplinary connections…" [6, p. 54]. Indeed, increasingly after the 1980s, 'convergence' has become a familiar term in conversations on science and engineering policy. This was, of course, a result of multiple factors that include the rise of 'Big Science' projects such as the Human Genome Project, the digital revolution across a range of scientific disciplines, and the growing awareness of the interconnected nature of scientific, environmental, and social challenges.

While the idea of convergence offers a general framework for the generation and integration of knowledge that needs to exist beyond disciplinary boundaries, the initial emphasis was on the overlapping areas of technological research among nanotechnology, biotechnology, information technology, and cognitive science [8]. In 2016, the U.S. National Science Foundation, a major player in shaping the research agenda in the U.S., identified 'growing

convergence research' as one of the 10 big ideas for future research investments**.** Since then, the NSF's language of convergence has highlighted the societal impact and non-academic partnerships—what might look 'external' to a narrow definition of academic research—as the key aspects of what constitutes successful convergence.

Alongside this transformation in the language of 'convergence', the link between CR and education has evolved. In policy recommendations, the key aspect was initially identified as non-discipline-specific knowledge. For instance, in the 1990s, the OECD (Organisation for Economic Co-operation and Development) recommended that that "educational institutions…focus on developing transferable, domain-general knowledge, skills and capabilities" [15, p. 3]. In the 'Learning Compass 2030', released in 2019, the OECD broke from its previous stance "that treated disciplinary knowledge as outmoded" [16, p. 473] by emphasizing that disciplinary knowledge is "essential to knowing interdisciplinary knowledge" [16, p. 473]. The evolution in the OECD's recommendations was not surprising as it reflected a growing awareness that integration of CR into education is not simply a matter of figuring out an interdisciplinary—or transdisciplinary—curriculum.

Replacing the emphasis on the 'generalist' knowledge, the 'contextual' nature of convergence has come to be a key defining component of knowledge generation and application in CR. William Sims Bainbridge and Mihail C. Roco, two major theorists of CR, suggested, "[c]onvergence learners must not only acquire higher levels of knowledge than previous generations; they will also have to master it deeply enough to apply it in many different contexts" [11, p. 938]. While there still does not exist a consensus regarding the balance between disciplinary and cross-disciplinary curricula that could be most effective for supporting the goals of convergence research, there are two major skills that seem to receive the spotlight in the

current formulations of CR: 1) understanding the *context* of a problem by co-evaluating relevance, priorities, and risk with stakeholders, and 2) co-developing solutions that can be implemented and sustained within the same *context*. In that respect, the existing literature is almost unified in highlighting the value of a cross-disciplinary education that prepares students to navigate epistemic *contexts* beyond academia while addressing the competing needs of stakeholders inhabiting those *contexts*.

It is important to keep in mind that, as Xuelong Hu recently claimed, this shift presents a rather instrumentalist view of research that is subject to the short-term demands of external partners. Hu adds:

> interdisciplinarity, associated with 'socially robust knowledge', 'societally relevant knowledge', or 'societal responsive knowledge', is designed to describe how socially constructed knowledge in 'the context of application' involves the contingent features of contexts as defined by external stakeholders. Far less attention is paid to the internal configurations underpinning interdisciplinary knowledge. [16, p. 473]

Against the rising interest in 'the contextual', we find Gajary et al.'s recent proposal helpful as they offered a definition of convergence as a **system of systems** [5, p. 2, 9]. Their expanded definition considers convergence research as an adaptive, dynamic process [5, p. 9-10]. While convergence research is always grounded in specific time and space, it cannot be fully described by any single process. Gajary et al. aimed to broaden the scope of convergence research (as an object of study) by framing it as a systemic phenomenon that itself emerges from semi-autonomous systems-level interactions and transformations across different knowledge domains. Specifically, their formulation includes three ancillary systems that are each linked by processes of "inter-system feedback and synthesis" [5 p.10]. These systems are (a) collaboration systems,

(b) inquiry systems, and (c) contextual systems—representing the interactions of (a) people, (b) research conduct, and (c) the social and physical ecosystem in which the research is conducted, respectively.

The system-of-systems model aims to provide an "expanded ontological perspective of Convergence Research as a complex adaptive system that dynamically interacts with collaboration, inquiry, and contextual systems" [5, p. 3] (see Figure 2). It offers not only a flexible perspective that is responsive to various external factors, but also a framework to understand those 'external' factors as part of 'internal' relations. In doing so, it opens up a new space for conceptualizing convergence research beyond, on the one hand, the insular definitions that only focus on academic knowledge generation and application and, on the other hand, the instrumentalist definitions that prioritize short-term demands of commercial stakeholders.

Some scholars suggest that the transcendence from which transdisciplinarity derives its name indicates that the subject of transdisciplinarity cannot be accurately described without the coordinates provided by scientific disciplines—which, paradoxically, means that transdisciplinarity cannot exist without disciplinarity [12, p. 187]. In this respect, the metaphor of boundary crossing is not very helpful in thinking about CR. The transdisciplinarity of CR is constituted by approaches that use epistemic frameworks built simultaneously between disciplines, across disciplines, and beyond all disciplines. The distinctive power of the system-of-systems model lies in its ability to turn the CR spotlight to the cumulation of interactive processes that exist at multiple disciplinary scales.

Convergence Research Training for Graduate Students

The graduate student research training program we focus in this paper has been funded by a National Science Foundation Research Traineeship (NRT) grant: NRT FORW-RD (**F**uture **o**f

Robots in the **W**orkplace—**R**esearch and **D**evelopment). The training program was built on the observation that dominant thinking regarding the future of robots is divided among techno-optimists and techno-pessimists. Despite their opposition, both of these camps are techno-determinists. They attribute historical agency to technologies. This presents a very narrow view of what humans can do to shape the future. The NRT FORW-RD program instead focuses on the need to create a new generation of engineers and technologists who can actively lead the transition to the future of work.

Such a focus on engineers and technologists starkly contrasts with the popular discourse around the future of work. From the World Economic Forum to OECD to the International Labor Organization, every major supranational organization has indeed something to say about the future of work. The big tech companies such as Microsoft and Google have dedicated research and development initiatives that are supposedly 'building' the future of work. McKinsey and other business consulting companies frequently produce reports on recent trends shaping the future of work. Even though the work of engineers and technologists—as they create technologies of the future—is the key to the future of work, their voices are rarely heard.

The NRT FORW-RD program provides a wide array of opportunities to develop technical and professional skills in graduate trainees. All of these opportunities centered on fostering convergence research skills: coursework, research collaborations, seminars and workshops, and broader impacts training. The 'convergent research' learning environment of the training program requires trainees to complete a research project that focuses on a particular aspect of human-robot interfacing, designed to assist people with the intersection of robots and the future of work. The trainees can select from a menu of courses across a range of disciplines that broaden their technical knowledge. The interdisciplinary coursework broadens the theoretical and

methodological perspective of the trainees. Additionally, the program requires each trainee to include a chapter on the broader impacts of research into their dissertations and theses. The program's required applied ethics course offers a collective intellectual space in which the trainees explore non-technical consequences of their technical research.

This paper presents a discussion of convergence research through the lens of the graduate student trainees. From October 2023 to February 2024, the coauthor Telliel interviewed 13 trainees (7 PhD and 6 MS students). These interviews were conducted remotely by using videoconferencing platform Zoom. The interviews primarily focused on the students' conceptualizations of convergence research, experiences of navigating between disciplinary research and convergence research, and the need for more effective strategies to support convergence research among graduate students.

Telliel was one of the principal investigators of the traineeship program. His expertise is in cultural anthropology and applied ethics, and he has taught the traineeship program's required course on the ethics of robots and AI systems. Some of the interviewees had taken or were taking his course when he conducted these interviews. Interviewees were not required to participate in these interviews. Indeed, some of the trainees were not able to participate because of their schedules. The coauthor Lydon is an undergraduate student majoring in mechanical engineering and applied mathematics. While he did not participate in interviews, he co-analyzed the interview data and contributed to the survey of the literature on convergence research. As a student with an interest in multidisciplinary inquiries, he was able to bring insights concerning the place and role of convergence research opportunities in engineering education.

Students' Definitions of Convergence Research

Before or during the interviews, the interviewer did not provide specific definitions of convergence research. Because the graduate students' responses tend to reflect their thinking, it was valuable for us to see overlaps across the students. 10 out of 13 interviewed students offered a total of 27 keywords that "defined" or "characterized" CR. These responses provided a snapshot of the students' personal beliefs about CR, which fell into three broad concepts: 1) CR values receiving feedback from many unique perspectives, 2) CR processes span disciplinary boundaries, and 3) CR relies on cooperation. The remaining keywords helped characterize both the benefits of a convergent approach and how CR is conducted.

Keywords that Describe Convergence Research		
Groupings and Underlying Beliefs	**Number of Uses**	**Related Keywords**
CR values receiving feedback from many unique perspectives	14/27	Applied, Broad, Collaboration, Diverse problem-solving, Fundamentally-integrated, Holistic, Multifaceted, Teamwork, Totally different ideas or solutions for the same problem
CR processes span disciplinary boundaries	11/27	Broad, Diverse problem-solving, Fundamentally-integrated, Interdisciplinary, Intersectional Multidisciplinary, Multifaceted
CR relies on cooperation	7/27	Collaboration, Teamwork
Keywords that contextualize CR	10/27	Applied, Broad, Complicated, Creation, Ever-expanding, Feeding-forward, Holistic, Mutually-reinforcing, Optimality, Totally different ideas or solutions for the same problem

The keyword responses from the interviewees align well with the System of Systems model [5]. Among the three systems, collaboration systems are most clearly represented by the keyword responses. Words like “collaboration,” “teamwork,” and “diverse problem-solving” directly connect the concept of CR to the researcher’s interactions. Their references to diversity and teamwork indicate that the interviewees view interpersonal relations as a driving force behind successful CR. Inquiry Systems were represented by keywords such as “mutually-reinforcing,” “interdisciplinarity,” and “fundamentally-integrated,” suggesting a focus on methodologies or epistemologies through which research is conducted. Contextual Systems found expression in keywords like “applied,” “holistic,” and “ever-expanding,” which highlight an awareness of the social and physical ecosystems in which CR operates.

Many of the student’s keyword responses, particularly repeated keywords like “collaboration,” “teamwork,” “multidisciplinary”, and “interdisciplinary,” resonate with the students’ emphasis on the feedback between researchers and other parties. This emphasis was so strong that these keywords appeared in each student’s response. These keywords align with the idea that CR, as a process, is not confined to a particular mode of inquiry or value system represented in any single discipline. It is important to highlight that this is not simply a matter of crossing boundaries between disciplinary spaces, but instead primarily a coming-together of modes of inquiry, each of which shapes the way researchers see and interact with the world they study. The graduate trainees indeed further spoke to the “ever-expanding,” “multifaceted” nature of CR, affirming the idea that multiple sources of knowledge (including those outside academia) must continuously co-evolve as they interact with each other.

The keywords such as “fundamentally-integrated” and “mutually-reinforcing” interface directly with the notion that CR requires both stabilizing and destabilizing feedback. Stabilizing

feedback is implied with the idea of "optimality" and "applied" outcomes through their assertion that some level of structural coherence is required to implement solutions in the real world. The presence of more open-ended keywords like "diverse problem-solving," "ever-expanding," and "totally different ideas or solutions for the same problem" reflects a flow of destabilizing feedback where existing frameworks are actively challenged.

Imagining Convergence Research as Feedback Flows

The theme of feedback represented a large portion of the interviews with graduate student trainees as they emphasized the role of their experiences as researchers. The trainees consistently showed an awareness that using feedback to alter the knowledge framework shared among researchers fundamentally shapes the convergence process itself. As a result of this awareness, the students frequently discussed the importance of using feedback to improve the research process. One graduate student captured how the very possibility of feedback—and the willingness to receive it—is fundamental to CR to the extent that one cannot initiate CR without it:

> Step one [to convergence research] is... being able to say "okay, I don't understand everything here, and I need to get feedback from other people."... I think [industry] does [this] more than academia does... Any commercial product already has some sort of feedback... Academia doesn't have [a channel of feedback] by default. The only feedback you get is when you submit a paper: you're told the paper's good enough or the paper is not good enough.

While the students' perspectives diverged with respect to who and what can give the most effective feedback, they consistently characterized other people's actual or potential contributions to their research through the lens of feedback. When asked about the value of convergence for his

own research, one student highlighted the significance of what becomes possible with perspective-taking:

> [New] perspective and expertise—the ability to ask questions that you yourself would not—is an important aspect [of convergence research] because... you, as an individual, are only the sum of your experiences. If you're adding another individual with a set of different experiences and an area that's very different from yours and trying to do something together that you both find meaningful... [it] is probably vastly different than what you yourself would have come up with if you were only integrating your own experiences.

Of course, valuing others' perspectives brings up an important question about the quality and nature of feedback a researcher might receive. For some graduate students, this question was reflected in their need to learn how to identify, evaluate, and navigate potential sources of feedback. The NRT FORW-RD program's emphasis on applied ethics and broader impacts of research played a significant role in spotlighting a world of 'feedback' that exists outside of the one inhabited by academic advisors and peers:

> The program has been helping people shift their mindset, look at other perspectives through things like the ethics class [and] the workshops. [It is an] undercurrent [and it] ends up sinking in even though it wasn't the main thing. [We now ask:] "who are the collaborators you think can help you on your project?" [This does not have to be] directly the people who would be working on the project alongside me. But it's a feedback thing. Who are people you could get involved [with the project] to provide you feedback on a perspective you don't have?

Many of the interviewed students expressed their interest in deliberately pushing the boundaries of one's comfort zone, as they believed that academic researchers focus so narrowly on their areas of specialization that they become constrained to those areas. As a student put it, "[the training program pushed them to] … come up with… projects… that might go outside the bounds of [their] own research." According to her, engaging with new research areas or expanding research into new areas (especially via establishing new feedback flows) interrupts a researcher's 'tunnel vision.'

The choice to engage with something that forces one to deviate from their "comfort zone" is an example of a flow of destabilizing feedback. This type of feedback permits an idea or experience to expand the boundaries of the researcher's epistemology. However, it does not necessarily enforce a particular direction of expansion—or methodology through which new knowledge and values are integrated with old ones. Consider a scenario where a research group—in which no member is an amputee—is studying how to manufacture prosthetic legs. If that group chooses to establish feedback to and from an amputee clinic, then this feedback will likely include knowledge that the researchers do not have. Hence, this feedback, in turn, has the potential to destabilize the group's existing perspective on research and development. Because the contacted amputees are potential end-users of the prosthetic, incorporating their needs, aspirations, and values into the research process can eventually shift the feedback flow from destabilization to stabilization.

Limitations on Convergence Research

One common concern that most of the interviewed graduate students reported was that they—as researchers—often operate within highly-structured and highly-regimented spaces of inquiry. Indeed, in the U.S. the dominant model of graduate STEM education is geared towards an

environment where the research inquiry is fundamentally shaped by funding concerns. For instance, one of the student trainees discussed the role of funding in this way:

> The faculty themselves [think like] “I want to see this project be a thing and I need someone from my lab. And, I really like this [other] faculty member to also join me, and we'll do something together. And, I expect two PhD students to work on this project for four years and get something nice out of it.” I think that goes back to the [question of] big grants. It's what [faculty researchers] are willing to write grant [proposals] for because [the funding agencies] are going to put resources on it, which is [their funded] PhD students.

For some students, this institutional context of STEM research culture incentivizes an attitude that aims to minimize the risk that is associated with something that might look unconventional. Such an attitude is, of course, not very well aligned with a genuine investment in the design and execution of convergence research. A student articulated it as a choice between different types of inquiries:

> A lot of the time, people are probably thinking “how can I integrate the work I'm already doing in some [convergence] research type thing?”, rather than trying to think of “maybe I could get together with somebody and we could try to start from the ground up and figure out what we could do to integrate our disciplines?.”... I just think a lot of people are probably going towards the easier route and just saying “I already have something, what can I do to just make this fit?” Or “what little tweaks can I make to try to tack on that convergent research even though it might be easier to just come up with something a little bit fresh.

Another student trainee mentioned that there is never sufficient time to tackle questions that are not related to the immediate research and writing projects that need to be completed. As the student highlighted, it puts the student in a less active role in designing new research inquiries:

> I needed to actually think through [how to think about convergence research]. When you are a PhD student especially, you are not thinking about some stuff [like question of convergence research] because you don't have time. And, you'd actually think about something when someone give you a task, which is crazy.

Given that none of the students had a theoretical and methodological understanding of convergence before they participated in the NRT FORW-RD program, the students' critiques of the contextual limitations are a result of the awareness they gained in the program. As students learned about CR and participated in CR projects, CR became an aspiration. The aspirational commitment to CR made them more aware of systemic limitations within higher education. Here is a student articulating that kind of critique:

> It's really hard to make some research to be convergent... You need a lot of time and planning and you need to be inspired by [the research] you actually want to work on...[The] majority of professors... Not just professors. All of us ... have tasks, [and] we want to finish [them], and that's it. But, I feel like a lot of, uh, professors are not ... engaged to make something convergent. They just want to fill a task that is [determined] by NSF or whoever else.

Engaging with destabilizing feedback in CR can be discomforting and lead to many uncertainties. As the student trainees acknowledged, even if graduate students are interested in engaging with CR, the institutional context of academic research operates as a stronger force of stabilization. It then becomes more challenging to embrace a culture of convergence research at a

larger scale. The openness to receive destabilizing feedback—the kind that the student trainees considered as a central element in CR—needs a different arrangement of research support infrastructure.

Within the current arrangement, however, one distinguishing characteristic of the graduate student researcher, as the interviewees thought about it, is an attitude of intentionality. Interestingly, the theme of intentionality appeared as frequently as a key component of CR—as much as, if not more than, theoretical and methodological preparation. For most of them, intentionality is the core of CR. Indeed, one graduate student trainee characterized it as "active collaboration as opposed to just passive working together." For another trainee, approaching CR with intentionality is the opposite of it being presented as a requirement:

> [Convergence] is probably the most valuable thing to me right now [as] I'm trying to push... to have a more well-defined convergence research section [in my project]. Not just [something] we could one day use. I actually [want to] do the thing. [Even though CR is] a great idea, but as soon as you put [it as a] requirement, everyone figures out what is the easiest possible thing I can do.

As a way of connecting academic work to something that is personally meaningful, CR has to be valuable in itself. He suggested that it did not need an external source of valuation, as that might steal away the appeal of the experiential dimension of CR. In this respect, looking at CR from the lens of feedback organically builds a framework that can center the experiential knowledge of the 'convergence researcher.'

Toward a Student-centered Convergence Research

We focus this paper mainly on the role and place of destabilizing feedback. In our interviews, most students valued feedback from their faculty advisors because their advisors' experiences

helped them limit their scope. This is indeed a very common manifestation of the feedback that stabilizes their research process. Stabilizing feedback also helped the graduate students obtain resources and gain legitimacy through the credibility of the systems of which they were a part. However, the interviewees also acknowledged the need to find sources of feedback external to their academic environment that could challenge their conceptions of an effective solution—that is, the kind of feedback that destabilizes their research process. Even though integrating this feedback required broadening the scope of their work, the students found value in critical reflection on their research problems and methods from a perspective that is not their own. These two flows, stabilizing and destabilizing feedback, work in tandem. CR requires destabilizing feedback to transform research inquiries into solutions more suited to changing real-world conditions. Yet, without stabilizing feedback, no CR project would ever approach completion. Furthermore, because individual researchers and their relations make CR possible, each researcher must learn to navigate both forms of feedback. Both feedback flows not only guide the alignment of research efforts but also ensure the research process can adapt to emergent constraints and requirements.

Among the students' responses, the infrastructure required to create and sustain convergence research at the graduate level was a recurrent theme. Moreover, this infrastructure was consistently related to the need for feedback that supports their CR efforts. According to them, the structure of graduate-level academia does not support CR in a robust way. The lack of institutional incentives—and in some cases, the presence of disincentives—can easily deter students from seeking CR-based projects. The interviewees' responses emphasized intellectual individualism, limited flexibility in coursework, and poor cross-departmental (or, even, cross-

laboratory) communication as significant barriers to building self-sustaining systematic feedback flows across campus.

While this is a study of a group of graduate students in one institution, it presents a view of convergence research from the perspective of graduate students. This is especially valuable as many systems-based models—while they are highly valuable—tend to overlook the experiential dimension of convergence research. By considering CR as a set of structured flows of feedback, we offer a framework that centers the researcher's experience in navigating across multiple systems they inhabit. In line with our phenomenological view, the students' interviews show a path into the lived experiences of CR researchers. Through the embodied, relational, and often improvisational aspects of research they discussed, the students drew our attention to CR as a cultural process that is not easily measurable by its academic outputs. By drawing attention to the convergence researcher, this framework can guide changes in research training programs for graduate students in engineering and related fields. It can guide adjustments of curricula toward communication and cooperation, and away from an exclusive focus on individual achievement. For convergence research to become a new paradigm (not simply a limited framework), the new generation of researchers needs to embody CR as an identity, outlook, and sensibility.

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