Student and Faculty Perspectives on Effectiveness of an Interdisciplinary Graduate Engineering Program

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***Abstract*— This Innovative Practice Full Paper presents findings from a qualitative analysis of student and faculty perspectives on activities designed to contribute to interdisciplinarity in a newly designed graduate engineering program; incorporating transferable skills (i.e., competencies needed to be successful in professional settings) throughout the curriculum. Current national trends suggest that materials development lags behind the technological needs of today. To address these concerns, an interdisciplinary graduate engineering program was designed, integrating transferable skills instruction alongside multi- and interdisciplinary coursework. Designed to emphasize the core principles of transformative learning theory (e.g., critical reflection, creative problem-solving, effective discourse, and authentic relationships), required program activities, like development of an ePortfolio, foster transferable skills acquisition in students. Continuous evaluation of program effectiveness is crucial in maintaining optimal program implementation and output. The current evaluation utilized qualitative analyses of student ePortfolios to better understand student and faculty perspectives of student outcomes based on interdisciplinary assessments of a cross-discipline design project. The results suggest that students acquired both transferable and technical skills through several unique program components and activities; further, skills acquisition appeared to contribute to successful completion of broader program learning outcomes. Implications for practice and future directions are discussed.**

Keywords—interdisciplinary, program effectiveness, graduate education, transformative learning

I. Introduction

Current national reports suggest that doctoral graduates should be equipped to navigate an interdisciplinary, collaborative, and global workforce to address present and future technological concerns [1, 2]. Projects like the Materials Genome Initiative (MGI), developed by the White House in 2011, showcase the need for interdisciplinarity in doctoral education [1], particularly when it comes to preparing the future workforce to successfully employ frameworks and concepts arising from the data sciences in the acceleration of the materials development cycle. Current trends suggest that materials design and development lag behind the technological needs of today [1]. The initiative proposed that collaborative efforts between materials science and informatics could accelerate advancements through big data analysis. Despite national propositions, traditional doctoral programs continue to train students for careers in academia, lacking in the transferable skills training necessary for widening the range of employment opportunities (i.e., industry-related positions) for doctoral graduates [3].

Not only do traditional programs lack necessary transferable skills training, but they also continue to promote overspecialization in a single discipline; deterring essential opportunities for the professional growth and interdisciplinary collaboration that is needed for innovation within materials development [4]. Materials science and engineering doctoral students are rarely exposed to computational analyses and methods needed for innovative design; similarly, informatics students typically do not obtain required domain-specific knowledge necessary for materials development.

Interdisciplinary programming in doctoral education is widely supported in the literature; however, the current program is both unique and innovative in that it employs transformative learning theory through the use of the Transformative Doctoral Education Model (TDEM) [5]. Initially grounded in Lattuca's sociocultural theory of learning, a review of the learning theory literature suggested that the current program appears to better align with transformative learning theory principles [5, 6, 7]. This theory suggests that adult learning develops through both a cognitive and affective transformation within each individual learner [6]. The transformation occurs through engagement in four key elements: 1) critical reflection, 2) creative and/or imaginative problem-solving, 3) effective discourse, and 4) fostering authentic relationships [8, 9].

For clarification, critical reflection is defined as critical awareness and assessment of assumptions as well as one's values, beliefs, judgments, and feelings; creative and/or imaginative problem-solving involves awareness and ability to recognize other perspectives, and creatively problem-solve using this new information; effective discourse requires taking all previous information and using it to gain new information through communication and collaboration with others; and authentic relationships employ awareness, critical reflection, genuineness, and knowledge of contextual barriers to promote positive relationship development between faculty and student [8, 9, 10]. TDEM utilized these core principles to create a new model for doctoral education; a full description of the model used to support the program

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outlined here is currently under review for publication [5]. With this framework, program components identified for participating engineering graduate students include disciplinary grounding and multidisciplinary coursework, transferable skill development, as well as an interdisciplinary design studio that allows students to utilize the knowledge and skills gained throughout the program to solve real world problems.

Aiming to investigate program effectiveness, the current study proposes that students' ePortfolios, which promote essential elements of transformative learning (i.e., awareness and critical reflection), demonstrate successful completion of program learning outcomes acquired through unique activities within this innovative, interdisciplinary program. It is hypothesized that faculty evaluations of students' final design papers, assessing for level of interdisciplinarity and abilities in critical reflection, will support the practice and application of those learned skills. Findings from the current study have implications both internal and external to the program. Foremost, such findings endorse improvements in program implementation; specifically, investigators aim to determine whether the design studio should be lengthened from one semester to two. More importantly, though, the overarching educational impact of such findings support the value and necessity of interdisciplinary scholarship in doctoral education.

II. Interdisciplinary STEM Doctoral Program: Design and Theory

This interdisciplinary program combines a cross-discipline curriculum, a design studio, and student learning and writing communities to provide students with a unique opportunity to engage in interdisciplinary collaborations and transferable skill development. The program was designed to address the aforementioned national concerns by producing well-trained, interdisciplinary scholars, across materials science, informatics, and engineering. Student participants are selected across six disciplines (Materials Science and Engineering, Mechanical Engineering, Chemical Engineering, Electrical Engineering and Computer science, Physics, and Chemistry), and are accompanied by faculty members, as advisors and mentors, from each discipline.

This two-year training model first engages students in disciplinary grounding and multidisciplinary coursework, then introduces interdisciplinary experiences through a design studio [7, 11, 12]. It is important to clarify the difference between multidisciplinarity, interdisciplinarity, and transdisciplinarity. While multidisciplinary programs provide brief exposure to several disciplines, interdisciplinarity implies collaborations from respective disciplines. Further, interdisciplinarity requires the utility of higher level problem-solving capabilities; being critically aware of 1) the gaps in one's own discipline, 2) the need for cross-discipline collaboration, and 3) simultaneously understanding other methods for solving those problems across disciplinary boundaries [13, 14]. Transdisciplinary programming, on the other hand, transcends each respective discipline to create a new field; a shared framework through fully integrating traditional disciplines. The current program utilizes both multidisciplinary coursework and interdisciplinary collaboration to ultimately enhance interdisciplinary mastery across fields.

To illustrate, Figure 1 showcases a condensed version of the full training model. As shown, students enter the program and begin coursework in their respective disciplines (e.g., Electrical Engineering, Material Science and Engineering, Mechanical Engineering). Next, students engage in multidisciplinary coursework (e.g., informatics, design, etc.,). Once formal coursework is complete, interdisciplinary collaborations are utilized to complete a final project through the design studio. Throughout their time in the program, students establish transferable skills through various activities to enhance professional and technical skills.

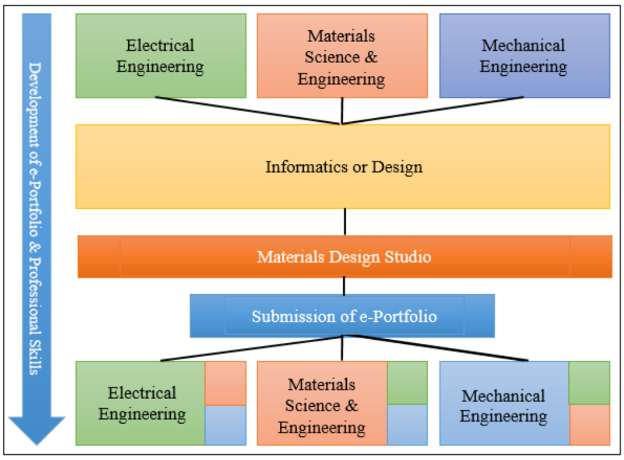

Figure 1. Condensed Version of Program Training Model.

Desirable skills of doctoral scholars were determined by a survey given to stakeholders (i.e., potential employers) to best understand expectations of future graduates (see Table 1). For the purposes of the current study, professional skills are equivalent to transferable skill as they are both competencies required for success across differing professional settings. Program outcomes were developed based on the professional and technical skills indicated as important for success across STEM fields (see Table 2). With the successful development of such a wide skill set, the program aims to produce multi-dimensional scholars prepared to accelerate technological advancements across materials science, informatics, and engineering design.

TABLE I. Desired Skills[a]

Professional Skills	Technical Skills
1. Critical thinking (**PS1**)	1. Application of core knowledge to interdisciplinary problems (**TS1**)
2. Interdisciplinary communication (**PS2**)	2. Design of computational/ physical experiments (**TS2**)
3. Interdisciplinary collaboration (**PS3**)	3. Application of informatics to materials science (**TS3**)
4. Ethical behavior (**PS4**)	4. Goal-oriented design of systems, components, processes (**TS4**)
5. Organization/management skills (**PS5**)	5. Hands-on experience and practical knowledge (**TS5**)

[a]The table is adapted with permission from [15]. Copyright 2017 American Chemical Society.

TABLE II. PROGRAM OUTCOMES[a]

	Program Learning Outcomes
1.	Master concepts and principles of his/her central discipline and apply this subject matter to solve problems/generate new interdisciplinary knowledge (**TS1-TS5**).
2.	Collaborate on an interdisciplinary team and resolve conflict (**PS2, PS3**).
3.	Critically self-reflect on interdisciplinary collaboration and research (**PS1, TS2**).
4.	Communicate ideas and results to disciplinary and interdisciplinary colleagues and students in both oral and written format utilizing current technology (**PS2**).
5.	Demonstrate ethical choices during research and collaboration (**PS4**).
6.	Design interdisciplinary research or project (**TS1, PS5**).
7.	Understand concepts/methodologies of corresponding disciplines (**TS1-TS5**).

[a]The table is adapted with permission from [15]. Copyright 2017 American Chemical Society.

Taken together, these constructs, embedded within all program activities, act as the theoretical framework for the program's design. For example, within student learning communities, transferable skills are developed by utilizing effective discourse and building authentic relationships between students, facilitators, and mentors. Another activity is the Individual Development Plan (IDP), a living document that includes a variety of open-ended questions that revolve around topics like research, teaching, skills development, as well as health and wellness (http://cte.tamu.edu/CTE/media/Images/Fillable-Forms-IDP-for-TAMU_v6.pdf). Completed annually, students then meet with advisors to discuss their responses as a means to foster an authentic relationship between advisor and advisee. Relevant to the current study, students are instructed to create an ePortfolio, a web-based curriculum vitae with detailed reflections on their individual experiences (e.g., coursework, research collaborations, program-related activities; https://sites.google.com/site/d3emeportfolio/). Once established, student ePortfolios are revisited and updated throughout their time in the program to promote critical reflection. The utility of ePortfolios in higher education is well-established in the literature; however, employing ePortfolios in interdisciplinary, doctoral education is sparse [14]. In addition to these activities, students also, complete an interdisciplinary design studio, where students collaborate on a cross-discipline project and final paper. Faculty advisors serve as experts within their respective fields, and subjectively assess interdisciplinarity across the collaborative teams.

Although there appears to be a connection between transformative learning theory (specifically critical awareness and reflection) and interdisciplinarity, analysis of student and faculty perspectives of transferable and technical skills development is needed to better understand, which program components appear to be contributing to overall program effectiveness.

III. METHODS

A. Participants

Participants included students from the first cohort of this interdisciplinary program who were recruited by faculty leaders on the award team from current research teams in their labs. Five doctoral students and four faculty members were recruited for this study. There were 7 males and 2 females; 6 Caucasians, 2 Asians, and 1 Latino. The final design project and paper included three groups; two interdisciplinary teams that spanned across three disciplines, and an individual student who worked alone. It should be noted that the faculty advisor of Student 4 in Team 2 did not complete the interdisciplinary assessment for their student; However, Faculty Advisor 3 completed the assessment for the project/team as a whole. Full descriptions of participants are provided in Table 3. Each student gave written informed consent to participate in program-related research prior to acceptance into the current program.

TABLE III. DESCRIPTIONS OF PARTICIPANTS

Group	Student	Discipline	Faculty Advisor
Interdisciplinary Team 1	Student 1	Chemical Engineering	Faculty 1
	Student 2	Materials Science & Engineering	Faculty 2
Interdisciplinary Team 2	Student 3	Physics	Faculty 3
	Student 4	Materials Science & Engineering	Faculty 3
Individual	Student 5	Chemistry	Faculty 4

B. Data Sources

Qualitative data were collected from two sources: student ePortfolios and advisor assessments of the level of interdisciplinarity in the final design project. As previously described, ePortfolios provide students the opportunity to critically reflect on their program experience, such as primary discipline and multidisciplinary coursework, program-related activities (i.e., learning and writing communities, etc.), and the design studio. The current analysis solely focuses on student reflections regarding unique program activities (i.e., learning and writing communities, IDP, etc.) and the design studio for several reasons. Previous reviews have indicated teamwork and communication are important outcomes for assessing interdisciplinarity in STEM programs [13]. Activities like the learning and writing communities were developed, specifically, to promote collaboration and the enhancement of transferable skills, which aligns well with those previously reported interdisciplinarity-related outcomes. The same review also suggested that critical awareness and critical thinking were relevant outcomes for assessing interdisciplinarity [13]. Although disciplinary grounding coursework can sometimes encourage teamwork, communication, and critical thinking, such outcomes are often a product of activities like the learning and writing communities and the design studio that require hands-on, face-to-face collaborations with fellow students and other faculty. For these reasons, student reflections based solely on foundational coursework will be excluded from the present analysis.

The second source of data includes the final design project assessments completed by faculty advisors. Faculty advisors are required to complete the final assessment to determine the level of interdisciplinarity of the final design paper. The assessment, developed by Mansilla and Duraising in 2007 [16], includes several open-ended questions asking faculty advisors to summarize the student's work, discuss disciplines emphasized within the project, and provide evidence for disciplinary integration (i.e., interdisciplinarity), as well as use of critical awareness and reflection.

C. Analysis

The current study employed deductive content analysis to determine notable themes (i.e., transferable skills) throughout students' ePortfolio reflections. Open coding methods were utilized to categorize emerging and recurring themes [17]. Additionally, faculty assessments of final design projects were analyzed to determine whether or not program activities impacted overall level of interdisciplinarity in graduate students.

IV. Results

Five main skills emerged from the student ePortfolio data: critical reflection, communication skills, building connections, academic writing skills, and exposure to unique experiences.

A. Student ePortfolios

1) Critical Reflection: To reiterate, critical reflection is defined as critical awareness and assessment of assumptions as well as one's values, beliefs, judgments, and feelings. Each of the five participants engaged in critical reflection with regards to a variety of topics. Most of the participants (4/5) discussed failures alongside successes (i.e., judgments), which demonstrates their abilities to critically think about their work and their skills so as to improve in the future. As one student put it:

"Reflecting on my talk, I think I appeared scattered and nervous. I need to find a better way to organize my thoughts and make things more coherent…In the future when I need to give talks at conferences, I will be sure to practice in front of my peers so I can get useful feedback before giving the presentation."

Additionally, critical reflection occurs when the learner becomes aware of and challenges previously gained knowledge [8]. Throughout the examined student ePortfolios, it was clear that students engaged in critical reflection as they were able to clearly delineate the usefulness of other disciplines in solving problems in the research (i.e., assessment of assumptions). Students were not only aware of the gaps within their own thinking, but openly accepted the utility of methods from other fields. This is exemplified within their interdisciplinary design projects, where all of the students employed informatics analytical methods to solve problems within their respective disciplines.

As previously mentioned, transformative learning occurs through both a cognitive and affective transformation. Interestingly, students' (3/5) use of emotionally charged vocabulary seemed to increase over time, suggesting that they were becoming more relaxed, open, and honest throughout the duration of the program. These participants indicated 'stress' in response to certain activities; although stress-induced responses are not ideal in evaluating a program, this evidence could potentially indicate a level of change or transformation in regards to emotional openness.

2) Communication skills: All five participants commented on the development of communication skills throughout the program. Further, all participants discussed the struggles and successes of communicating their research and discipline to fellow students outside of their respective fields. For example:

1) "Another exercise I thought was highly beneficial was giving a 10-minute talk to our peers related to our discipline in order to teach them something new. Instead of presenting on something very specific, I decided to give a more general talk about a numerical method to solve second order differential equations. I figured, since all of us use differential equations in our fields, it could be useful to my peers."

Of note, this participant tailored their presentation to their peers, and attempted to find a common language to easily convey the concepts. The search for developing a common language was a unique subcategory identified within the overarching theme of communication skills. Such reflections clearly showcase students' attempts to engage in interdisciplinary communication.

3) Building Connections: All five participants mentioned relationship building with peers and/or faculty, as well as learning communities and coffee talks. Three participants spoke to the value of the coffee sessions; informal meetings with faculty and peers regarding an array of topics. One student wrote:

"These were extremely valuable to me because not only did it provide an opportunity to discuss these topics with professors that might not come up organically, it also provided a chance to get the perspective of multiple faculty on an issue. This is a rare privilege due to how bust [sic] faculty are you typically would only talk with your advisor in this way, if at all."

Each participant also commented on the networking opportunities made available through the program. Growth and/or development in these areas may be indicative of interdisciplinary collaboration within this cohort of students.

4) Academic Writing Skills: Three out of the five participants highlighted the importance of the writing community, but pointed more so to specific techniques and tools gained. Several students emphasized the value of the writing log and daily writing schedules, while others reflected on the peer review process and its benefits.

5) Exposure to Unique Program Experiences: Several participants (3/5) mentioned how much they appreciated a student forum with a Ph.D./M.B.A. industry-focused entrepreneur. Relevant to the current study, all three participants discussed how nice it was to talk to someone from industry rather than academia. One participant noted:

"Talking to Bryce was a cool experience because in my academic career thus far the most speakers are also academics whereas Bryce, although still a PHD, had the unique experience of founding a startup and being an entrepreneur…This new insight I've gained helps me understand that a startup is a potential career option given the right idea as long as I take into consideration all components of making a successful company."

The participant emphasizes a current issue in doctoral education today; many students may feel as though a career in academia is the only option until they are exposed to other opportunities. It may be important for doctoral programs to continue exposing students to successful and knowledgeable individuals from both academia and industry-related positions.

B. Interdisciplinarity Assessments

All faculty indicated high levels of interdisciplinarity across projects. Each of the faculty advisors pointed towards specific graphs, features, models, or frameworks within the project that subjectively evidenced the use of interdisciplinarity. For example, Faculty Advisor 3, a member of the Physics department, wrote the following:

"The different disciplines were well integrated and not specifically segregated within the description of the project. Materials science concepts of processing-structure-property and general features of the microstructure formed an important basis for the analysis, as did the materials-as-systems framework, and the physical/electronic properties underlying the thermoelectric behavior being discussed and optimized here. A large number of different statistical models were utilized within the informatics scheme for this project."

When asked to list selected disciplines and their appropriateness within the designs, all faculty advisors identified integration of informatics approaches and methods within project designs. Three of the four advisors specifically indicated that informatics integration allowed students to enhance their research, and solve problems in more advanced ways, respective to their fields (Chemistry, Chemical Engineering, and MSEN). Further, faculty advisor's assessments reveal completion of all the technical skills discussed previously in this review. In regards to goal-oriented design and sense of purpose, only three of the four advisors reported students' clarification of purpose and evidence of critical awareness. Of note, Faculty Advisor 2 noted:

"Throughout the project, students were continually forced to reflect on the strategies chose [sic] in order to complete the project and were forced on many occasions to change track, depending on the (expected) difficulties associated with the project. I believe that they are fully aware of the potential as well as limitations of the approach followed by them."

However, Faculty Advisor 1 disagreed. Faculty Advisor 1 reported that improvements were needed in regards to developing a clear sense of purpose, and more clearly specifying the utility of informatics methods. It was noted that Team 1's project was conducted in Faculty Advisor 1's lab. It is possible that this advisor's criticisms may be due to differential involvement in the students' design project.

V. Discussion

Doctoral education, as it currently stands, is lacking; programs that promote interdisciplinarity are needed at the forefront of materials sciences to produce scholars prepared to meet the technological demands of today. To address these concerns, an innovative, interdisciplinary materials science and engineering program was developed. Utilizing a transformative learning framework, the current program provides students with opportunities to hone both their cross-discipline technical skills and the transferable skills necessary for career success. Unique to this program is student-centered activities to promote community and self-reflection; examples of such activities include student learning and writing communities, completion of an IDP, as well as development of an online ePortfolio. In order to examine the effectiveness of these unique program components on completing program learning outcomes, a qualitative analysis of student perspectives was conducted.

Four of the five transferable skills-related outcomes were met based on student responses. Specifically, students engaged in critical reflection and strengthened their own communication skills. Further, students collaborated on an interdisciplinary project with fellow students across disciplines. Organization and management skills were emphasized through student discussions of the writing community; gaining tools like writing logs to schedule set times for completing writing tasks. Ethical decision-making, on the other hand, was very rarely mentioned in student responses. One student discussed the benefits of the ethics seminar provided by the program, and touched on the importance of ethical decision-making in research, but did not mention these points specifically in concerns with the design project. It is possible that qualitative analyses do not capture the nature of ethical decision-making, and its use within student's final design projects or through the unique activities offered by the program. On the other hand, though, a single semester-long design studio may not sufficiently prepare students to engage in ethical decision-making on collaborative teams. Additional research is needed to better understand the utility and implementation of explicit instruction of ethical decision-making within the current design studio.

Based on faculty assessments, it appears that students employed each of the technical skills, outlined by stakeholders, in completing an interdisciplinary materials design project. Of note, faculty emphasized the importance and utility of informatics-based methods in students' projects. Further, faculty advisors evidenced appropriate integration of disciplines across projects. There were some discrepancies, though, in clarity of purpose in designs, which is indicative of goal-orientedness. The faculty advisor reported that students could have done a better job justifying and critically reflecting on their study. However, it was noted that the students conducted the study in that faculty advisors lab, which may have impacted advisor responses.

Overall, both student and faculty perspectives demonstrate successful development and implementation of most transferable and technical skills targeted within this innovative, interdisciplinary program. One skill that was not necessarily emphasized was ethical behavior, which may have occurred for several reasons. Firstly, explicit instruction and discussion of ethical behavior within the program are limited, which restricts students' opportunity to reflect on those activities. Secondly, even if students engage in ethical behaviors, they may not know how to critically reflect specifically on those behaviors. Individual student interviews may address these concerns, suggesting the need for further study. It is possible that additional ethics-related activities should be included in the program to target these specific skills.

VI. Limitations

One major limitation of the current study is the sample size. Characteristically, empirical studies require calculable, large sample sizes with the hopes of generalizing findings to the greater population. However, the literature suggests that sample size determination in qualitative research is largely based on contextual factors, rather than pre-specified estimates [18]. To illustrate, the size of the current cohort ultimately determined the sample size, as only 5 students, and 4 faculty advisors, were directly involved at the time. Although a still heavily argued topic, some qualitative scholars suggest that a sample size of 20-30 is appropriate, while others indicate that as little as 10 may be adequate for study [18].

The deceptively simple solution for addressing this limitation involves increasing cohort size; however, negative cascading effects could impact both program implementation and outcomes. For example, higher rates of student recruitment and participation require more faculty and staff to appropriately support those students, which, in turn, drives significantly increased funding needs. To mitigate these concerns, other solutions should be considered.

Specifically, the overarching concern lies in the differential between qualitative and quantitative research standards. Generalizability in qualitative research can be achieved through data saturation or when "no new information of themes are observed in the data from the completion of...interviews or cases [19]." Although methods for reaching saturation vary in the literature, some suggest that utilizing structured questions (e.g., providing the exact same prompts for each participant) is sufficient [20]. Such methods were employed within the current study, potentially negating the necessity of increasing sample size.

VII. Future Directions

In review of the program outcomes, the data suggest at least six of the seven outcomes are being successfully completed through the interdisciplinary design studio and unique program activities that promote transferable skills. As previously mentioned, though, ethical behavior was sparsely discussed within student ePortfolios. It is possible that one semester of instruction in the design studio does not fully equip students with the ethical knowledge needed to be successful in interdisciplinary collaborations. It is likely, then, that the design studio coursework and/or curriculum should be adjusted to better emphasize the importance of ethical decision-making in collaborative settings.

In regards to national concerns in materials design, there is still some uncertainty about how the current program impacts larger global and societal influences. For example, professional success cannot be assumed to be directly related to program completion. For these reasons, future studies should include a follow up of students after graduation with a survey of current job positions. Employment across a variety of professional settings (i.e., academia, industry, government labs, etc.,) would offer additional supportive evidence of the effectiveness of the current program.

In a broader sense, the larger educational impact of the current study suggests that engaging in transferable skills-based activities, as well as a cross-discipline design studio, promotes interdisciplinarity in doctoral education, as supported by transformative learning theory. Interdisciplinary programming, however, should not be restricted to STEM fields alone. Further studies are needed to understand the generalizability of interdisciplinary education across all disciplines. Development and study of efficient and effective interdisciplinary programming has the potential to change the face of doctoral education.

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