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Assessing Student Interdisciplinarity: Results from an Interdisciplinary Graduate Program in Science and Engineering Fields

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Abstract

To address national needs within materials discovery and development, a new interdisciplinary graduate program was designed at the intersection of materials science, informatics, and design. As the first cohort students completed the two-year training and submitted their final interdisciplinary research, the current study employed several different approaches to assess the level of student's interdisciplinarity. One approach, which differentiates from the mainstream approach of creating and utilizing rubrics, was presented in this study. Specifically, level of interdisciplinarity was evaluated by analyzing citations used in a final design process as well as conducting a social network analysis. The results revealed that the research projects conducted by interdisciplinary teams displayed higher levels of interdisciplinarity in comparison to a single disciplinary team (i.e., all members from one discipline). The findings suggest that this interdisciplinary program may provide advantageous opportunities for doctoral students to cross disciplinary boundaries in materials discovery and development.

Introduction

Within traditional graduate education programs, students acquire and develop discipline-specific knowledge, skills, and values with little focus on collaboration and exploration outside one's field or area of expertise. Solutions to the complex problems of today, though, often fall between or across disciplinary boundaries; suggesting the need for current graduate education models to span interdisciplinary research collaborations and innovative problem-solving processes to find unique and creative solutions to society's most pressing concerns.

Trends within the field of materials science suggest that, materials development is often too slow in providing practical solutions for the current needs of technological advancement [1, 2, 3, 4]. Given this, the Materials Genome Initiative (MGI) was announced by the White House in 2011; this initiative posed that the synergistic combination of experiments and simulations through an informatics framework would speed up advancements in materials discovery and development utilizing big data [1]. Unfortunately, current materials science and engineering students often receive minimal training in statistical principles and methods, computational analysis, and sophisticated programming. Likewise, students with stronger informatics-related skills are familiar with concepts and methods of engineering systems design, but do not have sufficient domain knowledge to solve materials-focused problems [2, 3].

To fill this gap across disciplines and using new analysis techniques, a new interdisciplinary graduate program was designed at the intersection of materials science, informatics, and design. In the first year, recruited students from science and engineering fields were grounded in primary disciplines; the second year students develop a broader knowledge base through multidisciplinary courses in new content areas of informatics, materials science, and design and finally conduct an interdisciplinary research project in the materials design studio. During these two years, the program provides students with opportunities to develop professional and technical skills through student learning communities, writing sessions, coffee talks, and a series of seminars. Through these experiences, the program creates a collaborative platform for students and faculty members to transcend disciplinary barriers.

The aim of the current study is to evaluate the level of interdisciplinarity across trainees within this innovative program. The use of citations within a final design-related paper were analyzed in order to evaluate and determine the level of student interdisciplinarity [5, 6, 7]. Three indicators of interdisciplinarity, such as variety (i.e., the number of disciplines), balance (i.e., the evenness of distribution), and disparity (i.e., the degree of difference) are utilized within the current literature [5, 6, 7]. Given the fact that disciplinary doctoral students conduct studies with their advisors and, thus, within domain-specific labs and/or programs [8], we hypothesize students have similar research domains as their advisers and faculty within the same discipline. Discrepancies outside of common disciplinary research domains between students and faculty could be evidence to support that students are successfully crossing the disciplinary boundaries. Therefore, assessing such disparities could potentially provide quality indicators of the interdisciplinary graduate education program.

For this study, participants were recruited from the materials design studio where students are required to complete an interdisciplinary research project. The participants were grouped into two interdisciplinary teams (i.e., program trainees across different domains), one Disciplinary team (i.e., both students were from the Materials Science and Engineering department), and a single individual (i.e., one student who completed the project independently). Bibliographic references in participants' final papers were analyzed to determine research domains involved; research domains of faculty members were identified by their personal publication records. This data examined discrepancies between the domains of faculty members and students. Further, comparisons between teams were conducted. Findings could indicate whether this interdisciplinary program provided trainees with the capacity to cross disciplinary boundaries in materials discovery and development.

The Design of an Interdisciplinary Graduate Program

Funded by an external grant, this interdisciplinary program recruited the first cohort of doctoral students in Spring 2016. The goal of the program is to develop the next generation of interdisciplinary scientists poised to make significant advances in materials discovery and energy-related materials design. Twelve faculty members from 6 departments (Materials Science and Engineering, Mechanical Engineering, Chemical Engineering, Electrical Engineering and Computer Science, Physics, and Chemistry) encompass the project team. Student participants are selected from these six disciplines. The program aims to train 80+ graduates in the five years of the program [2, 3].

The curriculum contains Disciplinary Grounding, Multidisciplinary Courses, an Interdisciplinary Course and Research [2, 3].

Disciplinary Grounding: During their first year of graduate studies, students focus on their individual disciplines to learn fundamental concepts, methods, and theories; including stewardship (i.e., agency and promotion) skills of respective disciplines. Following this stage, students are expected to contribute disciplinary knowledge accurately and effectively.

Multidisciplinary Courses: In the first semester of the second year, students are exposed to multidisciplinary courses, including advanced product design, materials informatics, and materials science, where students learn concepts identified as critical to the new interdisciplinary focus. During this stage, students begin to interact across disciplines through projects in the multidisciplinary courses ultimately preparing them for future interdisciplinary research.

Interdisciplinary Courses and Research: In the second semester of the second year, students engage in interdisciplinary research in a required materials design studio. Materials design studio is a project-driven studio course based on the integration of informatics and engineering systems design to address real-world problems in materials discovery and development. At the end of the semester, student teams are expected to present interdisciplinary research projects and submit final papers. The interdisciplinary research projects serve as one piece of evidence of creating a successful interdisciplinary program.

To provide a collaborative learning platform and break down disciplinary barriers, during the training process, students are required to participate in a learning community, writing community, coffee talks and seminar series also designed to enhance professional and technical skills (see Table 1). Students are mentored through the use of an Individual Development Plan (IDP), which facilitates student self-reflection, goal setting, and career planning supported by annual discussions of the student and advisor [2, 3].

Table 1. Desired Skills.

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

Note: The table is adapted with permission from [4]. Copyright 2017 American Chemical Society.

Methods

Participants

Seven doctoral students and seven faculty members were recruited for this study. As shown in Table 2, these students (student 1 - student 7) consisted of 4 research teams, including 2 Interdisciplinary teams, 1 Individual team, and 1 Materials Science & Engineering (MSEN) Disciplinary team.

Interdisciplinary team 1, Interdisciplinary team 2, and Individual team members encompass trainees of the interdisciplinary program. They have been grounded in their discipline, taken multidisciplinary courses, and participated in the Materials Design Studio. In one case, a student chose to work alone based on a unique research focus. Trainees in Interdisciplinary team 1 and 2 came from different disciplines and were advised by different faculty members.

Table 2. Student Participants.

Team	Student	Gender	Program	Advisor	Label (used in the network graph)
Interdisciplinary Team 1	Student 1	Male	Chemical Engineering	Faculty 2	IT1-CHEN+MSEN
Interdisciplinary Team 1	Student 2	Male	Materials Science & Engineering	Faculty 5	IT1-CHEN+MSEN
Interdisciplinary Team 2	Student 3	Female	Physics	Faculty 3	IT2-PHYS+MSEN
Interdisciplinary Team 2	Student 4	Male	Materials Science & Engineering	Faculty 4	IT2-PHYS+MSEN
Individual Team	Student 5	Male	Chemistry	Faculty 6	IT-CHEM
Disciplinary Team	Student 6	Male	Materials Science & Engineering	Faculty 5	DT-MSEN+MSEN
Disciplinary Team	Student 7	Male	Materials Science & Engineering	Faculty 5	DT-MSEN+MSEN

The MSEN Disciplinary team served as a comparison group, analyzing collaboration within the same discipline as opposed to interdisciplinary. The students came from the same program (i.e., MSEN) with the same advisor, who was also the instructor of the Materials Design Studio.

Table 3. Faculty Participants.

Faculty	Gender	Program	Label (used in the network graph)
Faculty 1	Male	Mechanical Engineering	F1-MEEN
Faculty 2	Female	Chemical Engineering	F2-CHEN
Faculty 3	Male	Physics	F3-PHYS
Faculty 4	Male	Materials Science & Engineering	F4-MSEN
Faculty 5	Male	Materials Science & Engineering, Mechanical Engineering	F5-MSEN/MEEN

Faculty 6	Male	Chemistry	F6-CHEM
Faculty 7	Male	Electrical & Computer Engineering	F7-ECEN

Seven faculty members from the interdisciplinary program were recruited for this study. As shown in Table 3, these faculty members came from Mechanical Engineering, Chemical Engineering, Physics, Material Science and Engineering, Chemistry, and Electronic and Computer Engineering. Table 4 shows that the faculty members with students in the past two years in various capacities including as instructors of courses, leaders of coffee sessions, and conducting seminars. Faculty 1, Faculty 5, and Faculty 7 were the course instructors, while Faculty 2, Faculty 3, Faculty 4, Faculty 5, and Faculty 6 were the advisors of students. We recruited these faculty members into this study because the formal and informal interactions between faculty and students within this interdisciplinary program may influence students' research focus.

Table 4. The formal interaction between faculty and students

Teams	**Interdisciplinary Team 1**		**Interdisciplinary Team 2**		**Individual Team**	**Disciplinary Team**	
Members	Student 1	Student 2	Student 3	Student 4	Student 5	Student 6	Student 7
Stage 1 Disciplinary Grounding	Faculty 2	Faculty 5	Faculty 3	Faculty 4	Faculty 6	Faculty 5	Faculty 5
Stage 2 Multidisciplinary Courses	Faculty 1 Faculty 7	Faculty 1 Faculty 7	Faculty 1 Faculty 7	Faculty 1 Faculty 7	Faculty 1 Faculty 7	N/A	N/A
Stage 3 Materials Design Studio	Faculty 5	Faculty 5	Faculty 5	Faculty 5	Faculty 5	Faculty 5	Faculty 5

Note. The program trainees interact with all faculty members from the other disciplines within the program during coffee talks, seminar series, etc.

Data collection

Data was collected to identify participants' research domains. For each doctoral student team, citations in final design studio research projects were collected. For each faculty member, publication records appearing in Web of Science were collected.

UCSD Map of Science, a classification system defining the unique domain of each of over 25,000 journals in the world [9], was employed to identify the research domain. The advantage of this system is vast coverage of the journals in the world, whereas the disadvantage of this system is new journals appearing after 2010, conference papers, and book chapters are not included. Despite the disadvantage, UCSD Map of Science is still one of the best solutions for this study. Table 5 shows the total number of domains identified by the UCSD Map of Science in our data. The missing data ranged from 15.4% to 68.2%.

Table 5. The percentage of identified publications and citations.

Faculty	Identified publications	Percentage of missing data
Faculty 1	70/84 (83.3%)	16.7%
Faculty 2	41/72 (56.9%)	43.1%
Faculty 3	44/52 (84.6%)	15.4%
Faculty 4	9/14 (64.3%)	35.7%
Faculty 5	84/107 (78.5%)	21.5%
Faculty 6	76/117 (65.0%)	35.0%
Faculty 7	45/91 (49.5%)	50.5%
Student Teams	**Identified citations**	**Percentage of missing data**
Interdisciplinary Team 1	15/31 (48.4%)	51.6%
Interdisciplinary Team 2	24/61 (39.3%)	60.7%
Individual Team	7/22 (31.8%)	68.2%
Disciplinary Team	30/55 (54.5%)	45.5%

Analytic Strategies

Two analytical methods were employed within this study. The first strategy utilized the measurement of cosine distances to assess interdisciplinarity among students and faculty in the program. An additional statistical technique, social network analyses, was used to determine research domain similarities between students and faculty.

Assessing Interdisciplinarity

The main indicator of interdisciplinarity for this study is "Disparity", which was calculated using cosine distance between 4 student teams and 7 faculty members [4, 5, 6]. The hypothesis predicts that, compared to the disciplinary team, research domains of the interdisciplinary teams would have smaller disparities to those of faculty from other fields, and larger disparities to their advisors and faculty studying in the same field.

To compute the cosine distance, the first step is to produce an original matrix that describes the proportion of each research domain for each team and faculty. The second step is to normalize the matrix by dividing each entry by the length of the given vector (square root of the sum of squares). The third step is to use the normalized matrix to compute the cosine similarity based on the following formula:

$$Similarity = \cos(\theta) = \frac{A \cdot B}{\|A\|\|B\|} = \frac{\sum_{i=1}^{n} A_i B_i}{\sqrt{\sum_{i=1}^{n} A_i^2}\sqrt{\sum_{i=1}^{n} B_i^2}} \quad , \tag{1}$$

where ||.|| represents Euclidean length of each feature vector. Ai and Bi are components of vector A and B. A stands for student teams, while B stands for faculty members. For the last step, the cosine distance is calculated by

$$Cosine\ Distance = 1 - s_{ij} \quad , \tag{2}$$

where s_{ij} is cosine similarity between each pair of student teams and faculty members. The value ranged from 0 to 1. A larger distance implied a larger disparity between a faculty member and a student team.

Social Network Analysis

Employing Google Fusion Tables to display the interactive graph, how student teams' research domains differed from their advisors' domains or the same-field faculty members' research domains was measured using the network graph. The graph characterizes networked structures in terms of nodes (i.e., faculty members, student teams, and research domains) and connecting edges indicate the affiliation between nodes. The distance between faculty members and student teams identifies the level of similarity of the research domains.

Results

Assessing Interdisciplinarity

Original Matrix

Table 6 represents the original matrix. The cell shows the percentage of each domain in the citation or publication for each team or faculty. For example, the MSEN disciplinary team tended to cite journal articles from Chemical, Mechanical, & Civil Engineering (73%); Faculty 1 from the Mechanical Engineering discipline frequently published journal articles in Civil Engineering (81%); Faculty 2, of the Chemical Engineering department, mostly published within Chemistry-related journals (93%).

Table 6. Original Matrix.

Teams/Faculty Domains	IT1	IT2	IT	DT	F1	F2	F3	F4	F5	F6	F7
D1	0.33	0.00	0.00	**0.73**	**0.81**	0.02	0.19	0.44	0.57	0.07	0.00
D2	0.47	0.38	0.57	0.00	0.00	**0.93**	0.10	0.11	0.00	0.75	0.00
D3	0.20	0.58	0.14	0.13	0.07	0.05	0.69	0.33	0.36	0.17	0.04
D4	0.00	0.04	0.14	0.07	0.04	0.00	0.02	0.00	0.05	0.00	0.51
D5	0.00	0.00	0.14	0.07	0.07	0.00	0.00	0.11	0.01	0.00	0.00
D6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.38
D7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
D8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
D9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07

Note. IT1=Interdisciplinary team 1; IT2=Interdisciplinary team 2; IT=Individual team; TT=Disciplinary team; F1=Faculty 1; F2=Faculty 2; F3=Faculty 3; F4=Faculty 4; F5=Faculty 5; F6=Faculty 6; F7=Faculty; D1= Chemical, Mechanical, & Civil Engineering; D2= Chemistry; D3= Math & Physics; D4 = Electrical Engineering & Computer Science; D5= Social Sciences; D6= Biotechnology; D7 = Medical Specialties; D8= Biology; D9= Infectious Diseases.

Normalization

To assess the disparity of research domains among faculty and student teams, the original matrix is normalized by dividing each entry by the length of the given vector (square root of the sum of squares). Table 7 illustrates the normalized data used to compute cosine distances.

Table 7. Normalized Matrix.

Teams/Faculty Domains	IT1	IT2	IT	DT	F1	F2	F3	F4	F5	F6	F7
D1	0.55	0.00	0.00	0.98	0.99	0.03	0.26	0.77	0.85	0.09	0.00
D2	0.77	0.54	0.92	0.00	0.00	1.00	0.13	0.19	0.00	0.97	0.00
D3	0.33	0.84	0.23	0.18	0.09	0.05	0.96	0.58	0.53	0.22	0.07
D4	0.00	0.06	0.23	0.09	0.05	0.00	0.03	0.00	0.07	0.00	0.80
D5	0.00	0.00	0.23	0.09	0.09	0.00	0.00	0.19	0.02	0.00	0.00
D6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.59
D7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00
D8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00
D9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10

Note. IT1=Interdisciplinary team 1; IT2=Interdisciplinary team 2; IT=Individual team; TT=Disciplinary team; F1=Faculty 1; F2=Faculty 2; F3=Faculty 3; F4=Faculty 4; F5=Faculty 5; F6=Faculty 6; F7=Faculty; D1= Chemical, Mechanical, & Civil Engineering; D2= Chemistry; D3= Math & Physics; D4 = Electrical Engineering & Computer Science; D5= Social Sciences; D6= Biotechnology; D7 = Medical Specialties; D8= Biology; D9= Infectious Diseases.

Cosine Distance

The calculation of cosine distance was based on Formula (1) and (2). Table 8 illustrates how each cell indicated the disparity of research domains between a faculty member and a student team.

Table 8. Cosine Distance.

Teams/Faculty Teams	F1	F2	F3	F4	F5	F6	F7
IT1	0.43	0.20	0.44	0.24	0.36	0.13	0.98
IT2	0.92	0.42	0.13	0.41	0.55	0.29	0.89
IT	0.95	0.07	0.65	0.65	0.86	0.06	0.80
DT	0.00	0.97	0.57	0.13	0.07	0.88	0.92

Note. IT1=Interdisciplinary team 1; IT2=Interdisciplinary team 2; IT=Individual team; DT=Disciplinary team; F1=Faculty 1; F2=Faculty 2; F3=Faculty 3; F4=Faculty 4; F5=Faculty 5; F6=Faculty 6; F7=Faculty 7. The value ranged from 0 to 1. A larger distance implied a larger disparity between a faculty member and a student team.

Disparity

The average distances were calculated between student teams and their advisors, student teams and the same field faculty, as well as student teams and faculty from the other fields (See Table 8). The results shown in Table 9 revealed that the Individual team and the MSEN disciplinary team had shorter distances to their advisor and the same field faculty members than Interdisciplinary teams 1 and 2. Although 4 teams showed large distances to the faculty from the other fields, the MSEN Disciplinary team also showed slightly larger distances with the faculty from the other fields than the Interdisciplinary teams 1 and 2. The results imply that the MSEN Disciplinary team show a lower level of interdisciplinarity than Interdisciplinary team 1 and 2.

Lastly, Individual team (trained by this interdisciplinary program) only consisted of one student, thus, the absence of interdisciplinary collaboration limited the level of interdisciplinarity.

Table 9. The Disparities with Advisors, the Same Field Faculty, and the Faculty of Other Disciplines.

	Distance to advisors	Distance to same field faculty	Distance to the faculty of other disciplines
IT1	0.28	0.27	0.71
IT2	0.27	0.50	0.53
IT	**0.06**	**0.06**	0.74
DT	**0.07**	**0.07**	**0.83**

Note. IT1=Interdisciplinary team 1; IT2=Interdisciplinary team 2; IT=Individual team; DT=Disciplinary team. The value ranged from 0 to 1. A larger distance implied a larger disparity between a faculty member and a student team.

Social Network Analysis

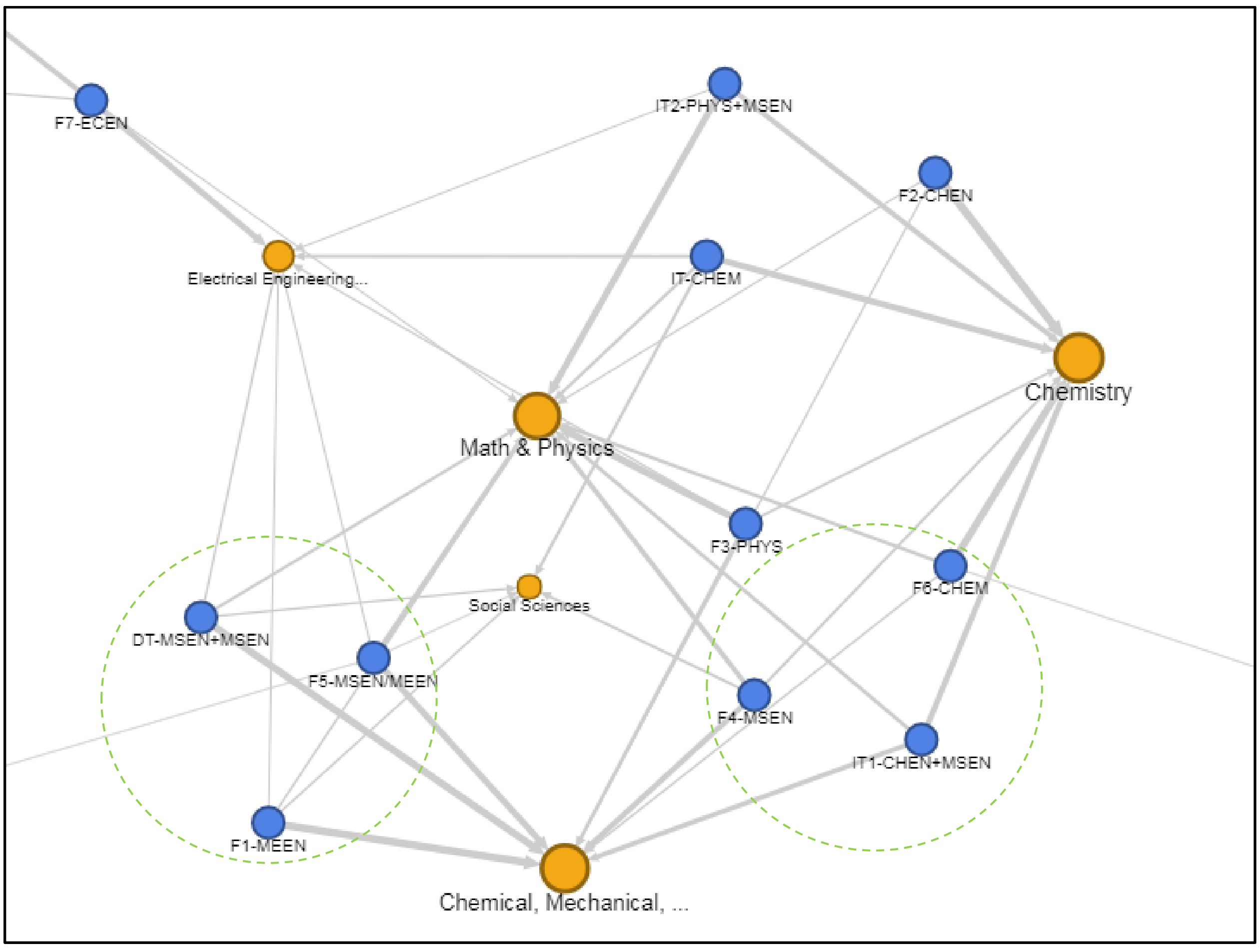

Figure 1. Network graph.

Note. The full version can be accessed at https://goo.gl/aAX1o3

The network graph illustrated in Figure 1 illuminates relationships among faculty and student teams. The full interactive version can be accessed via https://goo.gl/aAX1o3. Blue nodes indicate all faculty members and student teams; yellow nodes indicate research domains. The edges point out the research domains of each person. The thickness of each edge was weighted by the percentage of each research domain in each faculty member's publications or in the references of each student team's final paper. The larger yellow nodes implied research domains that appeared frequently; specifically, Math & Physics, Chemical, Mechanical, & Civil Engineering, and Chemistry were identified as highly cited or widely published fields.

The closeness of blue nodes also implies their similarity (see green dashed circles in Figure 1). Note that the members within the Disciplinary team had shorter distances from faculty 1 and faculty 5 all of which are from similar fields. This reveals that the disciplinary team's research project was mainly focused on topics within their primary discipline. The other finding is that interdisciplinary team 1, from chemical engineering and materials science & engineering, showed short distances with the faculty members from similar fields (chemistry and materials science & engineering); further implicating that their research project integrated both disciplines (chemistry and materials science & engineering), which aided in their interdisciplinary collaboration.

Discussion

The purpose of this study is to assess the interdisciplinarity of students based on citations utilized in their final research projects. Research domain disparities between students and faculty members were used to measure interdisciplinarity. One, single-discipline team (i.e., Disciplinary team) was recruited as a comparison group. The results suggest that Interdisciplinary teams demonstrated higher levels of interdisciplinarity.

Findings from the current study highlight two potential influences on students' level of interdisciplinarity. Firstly, participation in a multi-disciplinary curriculum allowed students to broaden their knowledge-base and perspectives on interdisciplinarity. This is evidenced by the cosine distances, which revealed that interdisciplinary teams' research domains were slightly different from their advisors' and same field faculty's research domains. Additionally, the network graph showed that these students location within the network were not close to their advisors; further suggesting that interdisciplinarity is heightened when cross-discipline team collaborations are utilized. Not surprisingly, the results of cosine distance and network analysis of the MSEN Disciplinary team showed that their identified research domains were quite similar to their advisors' and other faculty members within their field. Because the MSEN Disciplinary team had less opportunity for cross-discipline collaboration, their interdisciplinarity levels were insufficient. This finding suggested that the training process of the current program might strengthen both interdisciplinary learning and research collaborations.

Secondly, interdisciplinary collaboration appears to be an important component for enhancing interdisciplinarity in doctoral-level students. The findings of the current study indicate that the Individual team, which only consisted of one member, showed a very short cosine distance to his advisor and the faculty from his field; in other words, even though he participated in the interdisciplinary program, the levels of interdisciplinarity found within his final project were limited. Further, results from the network analysis showed that the Interdisciplinary team 1, which consisted of members across disciplines (i.e., Chemical Engineering and Material Science & Engineering), had shorter distances with the similar field faculty members (rather than their advisors); meaning that these students brought the knowledge from their respective fields into their research project. It is possible, then, that interdisciplinary collaboration may be a key component in conducting true, interdisciplinary research.

One considerable limitation of the current study is the missing data (15.4-68.2%) that resulted from misidentification of research domains across journal publications, book chapters, and conference proceedings. Identification of research domains within this study were based on the publication name, consultation with scholars in Library & Information Science, and by employing the UCSD Map of Science, which is the one of the best systems for identifying research domains for a wide variety of journals. Unfortunately, misidentification of publications and, subsequently, their respective research domain can oftentimes occur, and may not be the most appropriate measure for domain-related analyses.

This study provides a different perspective in interdisciplinarity measurement, which differentiates from the mainstream approach of solely creating and utilizing rubrics [10, 11, 12, 13, 14]. In today's society, current needs transcend disciplinary boundaries, and require more interdisciplinary research and development. The findings of this study suggest that interdisciplinary, graduate-level programming and collaboration may be the critical components for enhancing cross-discipline research, especially with STEM fields. Continued advocacy for the importance of utilizing interdisciplinarity to accelerate materials discovery and development are necessary.

With respect to future research, given missing coverage of citations, a mixed-method approach may be more appropriate for evaluating levels of student interdisciplinarity. For example, qualitative analyses may provide more detailed information on the quality of interdisciplinary research conducted within this program. Further, qualitative analytical strategies would also be useful for providing evidence regarding how each student's prior experiences (e.g., undergraduate training, prior work experience) and learning engagement in program activities (e.g., learning and writing communities) impact individual interdisciplinarity. Thus, further studies are needed in order to best understand these processes within engineering doctoral students.

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