An Interdisciplinary Graduate Education Model for the Materials Engineering Field

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Introduction

Materials innovations are crucial to technological progress. Unfortunately, the materials development is often slower than the timeframe over which technologies at the system level are created. In view of this, the Office of Science and Technology Policy of the White House released the Materials Genome Initiative (MGI) in 2011 [1], which indicates that the traditional materials development cycle is not the most optimal approach to addressing the lack of technology-enabling materials; instead, the better way to accelerate the discovery and development of materials is by the synergistic combination of experiments and simulations within an informatics framework [2].

This aspiration needs significant workforce development as the next generation of scientists and engineers should be able to connect materials data to better-informed materials synthesis and computational analysis, and use engineering design methods for the goal-oriented development of materials. However, current materials scientists, including those currently enrolled at universities around the nation, often get minimal training in data-related principles and methods. In the meanwhile, students with informatics-related skills who are familiar with concepts and methods of engineering systems design do not have the sufficient domain knowledge to solve materials discovery problems [2].

To fill the gap, a new interdisciplinary graduate program was designed at the intersection of materials science, informatics, and design. In this paper, we will introduce this education model, and discuss the initial results and implications. We hope this model can benefit other institutions, and produce a more productive materials workforce.

Interdisciplinary Education

The current higher education system mainly aims to develop students' knowledge and skills, isolated by traditional disciplinary boundaries. To overcome this limitation and create more possibilities for intellectual and professional development, the integration of multiple disciplines into the educational process is an alternative education strategy [3, 4, 5, 6]. Common terminologies describing the integration include *multidisciplinary* and *interdisciplinary*. *Multidisciplinary* features at least two academic disciplines which furnish different perspectives on a problem; however, this combination is less integrative [3, 4, 5, 6]. *Interdisciplinary, on the* *other hand, encompasses* a high degree of integration from at least two disciplines while addressing a real-world system problem. During the interdisciplinary research process, researchers from a variety of disciplines cross boundaries to solve the specific real-world problems and create new knowledge [3, 4, 5, 6].

Recognizing the potential of interdisciplinarity, national efforts, such as the Integrative Graduate Education Research and Training (IGERT) initiative, have emerged. The IGERT program, initiated in 1997 and terminated in 2012 funded 125 groups of faculty to “educate U.S Ph.D. scientists, engineers, and educators with the interdisciplinary backgrounds, deep knowledge in chosen disciplines, and technical, professional, and personal skills to become in their own careers the leaders and creative agents for change”[7].

Several studies describe the elements of interdisciplinary education including Borrego and Newswander who review the graduate-level IGERT programs at 98 institutions and indicate that the national efforts for interdisciplinary graduate education include: (a) grounding in multiple traditional disciplines, (b) integration skills and broad perspective of the interdisciplinary domain, (c) team work, and (d) interdisciplinary communication [5]. Boix Mansilla’s work includes development of rubrics which can be useful to assessing students’ interdisciplinary work. The performance criteria promoting interdisciplinarity in the rubrics include: (a) being well grounded in the disciplines, (b) advancing student understanding, and (c) showing critical awareness [8, 9]. To compare students’ interdisciplinary competence in engineering fields, Lattuca developed a measure for assessing students’ interdisciplinary competence, which consisted of three dimensions: (a) interdisciplinary skills, (b) recognizing disciplinary perspectives, and (c) reflective behavior [10]. Curricula for an interdisciplinary graduate education supporting many of the recommendations in the literature may include facilitation of student grounding in traditional disciplines, offering related courses in new chosen disciplines or conceptual areas to advance student understanding, and activities to develop students’ interdisciplinary skills (e.g., integration, teamwork, communication, critical thinking, reflection, etc.).

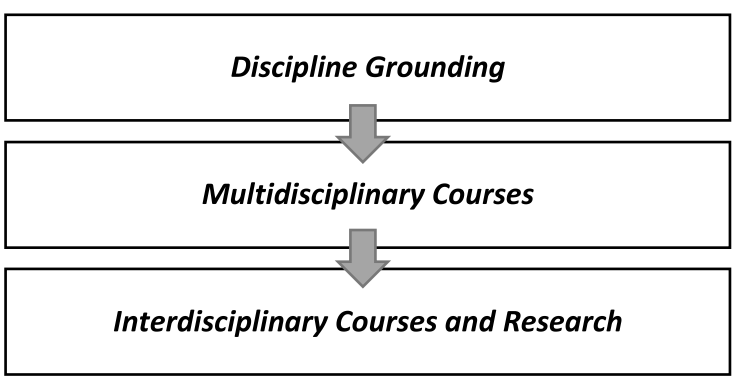

Figure 1. Conceptual framework for an interdisciplinary graduate education program.

The framework (Figure 1) of an interdisciplinary graduate education as described above illustrates an opportunity for students to be well-grounded in their primary disciplines first. Multidisciplinary courses or experiences begin a broader understanding in the fundamental concepts or methods of the new interdisciplinary approach and often require integration of the contributing disciplines as well as a critical awareness of the discipline shortfalls. Finally, students with the new conceptual and methodological toolkit participate in interdisciplinary design or research on real-world problems that require new interdisciplinary thinking including a continuous reflective behavior.

Program Development

In this study, we employ the conceptual framework incorporating the disciplinary grounding, multidisciplinary courses and interdisciplinary courses and research to develop a graduate education program for the materials engineering field. The interdisciplinary program described here and funded by the National Science Foundation in 2015, recruited the first cohort of graduate students in 2016.

Program Goal

The goal of the program is to produce a new generation of interdisciplinary researchers poised to make significant advances in materials discovery and design of energy materials.

Program Outcomes

The program outcomes, derived from a comprehensive survey of stakeholders, guide the development of the program components. The stakeholders encompass potential employers who have a good grasp of expectations for the graduates. The survey was completed by 65 potential employers (i.e., 12 academic, 28 private, 23 government, and 2 nongovernmental entities). The survey results (Table 1) reveal the most critical technical and professional skills desired by the employers and inform the program learning outcomes (Table 2).

Table 1. Desired Skills of Graduates.

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 from [11].

Table 2. Program Learning Outcomes.

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**).

Note: The table is adapted from [11].

Participants

Twelve faculty members from 6 disciplines (Materials Science and Engineering, Mechanical Engineering, Chemical Engineering, Electrical Engineering and Computer Science, Physics, and Chemistry) encompass the interdisciplinary project team. Student participants were therefore recruited from these six disciplines. Students were selected during recruitment to a discipline or in the first year of their PhD program where the disciplinary grounding occurs. The program will train 41 graduate fellows and 40+ additional certificate graduate students in the five years.

Tool Development

Three Ph.D. students from educational fields assist with the educational research under the guidance of an Educational Psychology graduate faculty member. In addition, one external evaluator with a highly experienced engineering education research background conducts the program evaluation every year. Tools developed to support learning and development of the participants include competency rubrics, individual development plan, and ePortfolio. Twelve competency rubrics assist in the assessment of program learning outcomes encompassing the proposed professional and technical skills, , including 1) interdisciplinary knowledge generation, 2) collaboration, 3) conflict resolution, 4) oral communication, 5) written communication, 6) self-reflection, 7) ethics, 8) interdisciplinary research, 9) multidisciplinary skills, 10) materials science engineering, 11) informatics, and 12) design. The rubrics were adapted from the literature and feedback from the project faculty customized them to the interdisciplinary materials science, informatics and design program (example in Appendix A). An Individual Development Plan (IDP) facilitates student self-reflection, goal setting and career planning as the

Table 3. The interdisciplinary graduate education program.

Curriculum & Activity	Timeline	Assessment	Rubric	Learning Outcome & Skill
Disciplinary Grounding	Year 1			
Summer School in Computational Materials Science	Summer 1			
Multidisciplinary Courses: Informatics, Design, Materials Science	Year 2	Course Projects	10, 11, 12	7. Understand concepts/methodologies of corresponding disciplines (**TS1-TS5**)
Learning Community ***Coffee Discussions*** ***Seminar Series***; ***Community of Scholars***; ***IDP ePortfolio***; **Interdisciplinary Course:** Materials Design Studio	Year 2	Course Projects	1, 2, 3, 4, 5, 9	2. Collaborate on an interdisciplinary team and resolve conflict (**PS2, PS3**) 7. Understand concepts/methodologies of corresponding disciplines (**TS1-TS5**) 1. Master the concepts and principles of his/her central discipline and apply this subject matter to solve problems and generate new interdisciplinary knowledge (**TS1-TS5**) 4. Communicate ideas and results to disciplinary and interdisciplinary colleagues and students in both oral and written format utilizing current technology (**PS2**)
Interdisciplinary Course: Internships	Summer 2	Projects	1, 4, 5, 8	6. Design interdisciplinary research or project (**TS1, PS5**)
Energy / Entrepreneurship	Summer 2			
Submission of ePortfolio	Summer 2	ePortfolio	6, 7	3. Critically self-reflect on interdisciplinary collaboration and research (**PS1, TS2**) 5. Demonstrate ethical choices during research and collaboration (**PS4**)
Interdisciplinary Research Thesis (Go back to their own discipline)	Year 3+	Research Thesis	8	6. Design interdisciplinary research or project (**TS1, PS5**)

student and advisor meet to discuss on an annual basis. The educational research team adapted an IDP template to align with the goals for the program. An ePortfolio serves as a composite for highlights of experiences throughout the program as well as written self-reflections by the students to articulate what they know and why they know it. The ePortfolio template has been created and published on Google sites.

Curricula and Activities

Using the conceptual framework as the basic structure and targeting the desired professional and technical skills, a curriculum of courses and various activities was designed. The curriculum includes Disciplinary Grounding, Multidisciplinary Courses, Interdisciplinary Courses and Research, Communities, and other activities as illustrated in Table 3.

Disciplinary Grounding: During the first year of graduate studies, students focus within their own disciplines to learn concepts, theories, methods, and forms of communication and stewardship of the discipline. After initial disciplinary grounding, students are expected to contribute disciplinary knowledge and methods accurately and effectively.

Multidisciplinary Courses: In the second year, students are challenged by multidisciplinary courses, including Advanced Product Design, Materials Informatics, and Materials Science where students are introduced to concepts of disciplines outside of their own. Advisors and course instructors identify knowledge and skill gaps within the three contributing interdisciplinary content areas of informatics, design, and material science utilizing the competency rubrics (10, 11, and 12). The advisors also give recommendations to the students on how to address the identified gaps to better prepare them for future interdisciplinary collaboration.

Interdisciplinary Courses and Research: After completing multidisciplinary courses, students engage in interdisciplinary collaboration and design in a required Materials Design Studio and an optional internship. In the Materials Design Studio, students work in interdisciplinary teams on real-world materials problems defined by industrial and governmental partners in consultation with faculty members, or linked to existing interdisciplinary research. Interdisciplinary knowledge generation, collaboration, conflict resolution, oral communication, written communication and interdisciplinary collaboration learning outcomes are assessed using rubrics (1, 2, 3, 4, 5, and 9) at the end of the course. During the summer, students will enrich their trainee experience by engaging in a situated learning experience involving real-world materials design and informatics problems with societal value through industry or government lab internships. In the third year, Ph.D. students go back to original disciplines and the hope is that they have gained a new interdisciplinary perspective that will expand their research vision and especially as it relates to energy storage, energy conversion, sustainability, and energy efficiency. Committee members will have the capability to measure the student’s ability to design interdisciplinary research and projects using the interdisciplinary research competency rubric 8.

Communities: Faculty members and students participate in communities of scholars and learning communities respectively. The Faculty Community of Scholars (COS) is a biweekly meeting that facilitates the development of a shared interdisciplinary culture, formulation and greater appreciation of interdisciplinary issues, collaboration, and partnerships, as well as maintenance of a communication cadence between members. At the same time, students participate in the Student Learning Community (SLC) that meets biweekly throughout the first year of the program. The SLC meeting assists students in the development of professional skills (see Table 1), and diminishes the gaps among disciplines through shared communication about individual disciplines.

Other activities: Students are expected to keep an ePortfolio throughout their experience where they describe knowledge and skills that they have gained and how they will benefit from them in the future. Students are mentored through use of an IDP which is discussed annually with the advisor and perhaps another mentor. Additionally, coffee sessions and seminar series are the platforms for informal interaction and the building of relationships among students and faculty members, as well as people outside of their networks. The program also furnishes the supplementary courses and activities including Energy/Entrepreneurship courses and an international summer school program in Computational Materials Science.

Lessons Learned

The main challenge of interdisciplinary programs is to help students work across traditional disciplinary boundaries. To overcome this obstacle, several studies pointed out the elements of interdisciplinary education [5, 8, 9, 10]; in particular, a review of the graduate-level IGERT programs at 98 institutions indicated that the existing interdisciplinary programs emphasize the well-grounding in home disciplines, broad perspective of the interdisciplinary domain, and interdisciplinary collaboration and communication [5]. This program design not only adopts the suggestions from the literature and potential employers, but also provides students and faculty members with unique activities, such as the COS, SLC, the IDP mentoring, self-reflective learning portfolio, Coffee sessions, Energy and Entrepreneurship courses, and Summer School in Computational Materials Science. The external advisory board also commented that the big difference from other interdisciplinary programs is that we have COS meetings to break the disciplinary boundaries.

As of now, two cohorts of students have begun the program. The first cohort enrolled a year and a half ago, while the second cohort started their first semester in spring of 2017. To examine the program's effectiveness, we collected data using surveys, observations, and class artifacts. Several findings are worthy of emphasis.

First, advisors play a critical role in student interdisciplinary learning. In this model, we rely on advisor support to facilitate student growth, development, and academic progress. Regular IDP meetings assist in making the strong connection between advisors and students which helps to support achievement of short- and long- term objectives. The advisor also aids in addressing gaps within the discipline. Competency rubrics are helpful to identify current ability, strengths, and gaps. Based on the results, advisors provide feedback and recommendations to students. Furthermore, advisors are kept up to date by participating in the COS meetings. We have observed that advisors who have low participation in the COS may have a negative impact on their students' engagement perhaps based on the lack of information that was shared during the COS of which they were absent. Therefore, we encourage advisors to attend the COS meetings regularly.

Second, COS meetings enable interdisciplinary collaboration and communication. The professional interaction was strengthened by review of the literature regarding interdisciplinary education, interdisciplinary curriculum design, creation and completion of twelve competency rubrics, discussion and development of assessment tools, structuring and executing the mentorship process and the IDP, usage and creation of student ePortfolios, and ideas/solutions brainstorming.

Third, support from education specialists benefits the program. The experts help effectively guide interdisciplinary components and curriculum structure as well as take the lead in the learning communities (i.e., COS and SLC). During the SLC sessions the students initially felt uncomfortable about data being collected for the education research. The education research was further discussed and clarified eliminating the concerns of the students. Overall, feedback regarding the education experts was positive, for example one student commented: "I really appreciate all the time the education folks have put into making sure we are successful." Students expressed that they enjoyed developing their professional skills with the educational experts in the SLC meetings.

Lastly, there was a tug-of-war between students' intradisciplinary identity and interdisciplinary identity. During a conflict resolution session students admitted that "the interdisciplinary program expectations are unclear", "they lack commitment with SLC's assignments", "they place these assignments on the bottom of the to-do list (relative to their disciplinary works)", "they need more reminders", and "they need a deadline". Despite this, most students still have met the requirements of the program thus far. Evidence indicates that interdisciplinary education faces an uphill struggle under the traditional disciplinary education framework especially when the interdisciplinary component is an 'add-on' to current disciplinary work. Similar findings appear in an interdisciplinary education experiment, the Snowbird Charrette [12].

Program Modifications

Two modifications for new cohorts of students have already been identified and implemented. First, an interview has been added during the recruitment process and is conducted by the project investigator (PI) and the educational Co-PI before students are accepted as program trainees. Questions and conversation focus on expectations, motivation, and commitments for the program including questions regarding plans for balancing priorities. Second, most students wanted to improve their academic writing skills, but few took ownership to write on their own. This is not unusual for busy graduate students, however programs exist to assist graduate students with becoming better academic writers so a decision was made to include such as effort. To that end, a graduate student writing consultant, one that has been trained in supporting graduate students in the writing process, has been brought in to conduct weekly writing sessions with cohort 2 where various topics are discussed and writing is peer reviewed. Students are required to engage in both the learning community and writing community in the future. We will continue to optimize the interdisciplinary graduate education program as we assess the results and determine next steps.

Conclusion

To produce the next-generation materials engineering workforce, we developed an interdisciplinary graduate education model, designed at the intersection of materials science, informatics, and design. The program design aligns with the recommendations in the literature, including facilitation of student grounding in traditional disciplines, offering multidisciplinary courses or experiences to advance student understanding, and participation in the interdisciplinary courses and research. However, under the traditional setting in higher education, students and faculty members are separated by disciplines. To assist in breaking down interdisciplinary barriers, faculty and students participate in learning communities (i.e., COS and SLC), which offer the opportunity for interaction of all discipline partners to share disciplinary perspectives, develop interdisciplinary skills, and position everyone on an interdisciplinary platform. To examine the program's effectiveness, we collected data using surveys, observations, and class artifacts. Several findings from the first cohort are noteworthy: (1) advisors play a critical role in student interdisciplinary learning; (2) COS meetings enable interdisciplinary collaboration and communication; (3) support from education specialists benefits the program; (4) students struggle with the interdisciplinary learning due to their disciplinary identity developed by years in the discipline. Two modifications for the new cohort have already been identified and implemented: (1) an interview, focusing on expectations, motivation, and commitments, has been added during the recruitment process; (2) recognizing the importance of writing skills, a writing community for students has been facilitated. We hope this program will assist in producing the next generation of materials engineers and scientists.

References

1. C.H. Ward, C.H. Ward, and J.A. Warren, *Materials Genome Initiative: Materials Data* (U.S. Dept. of Commerce, National Institute of Standards and Technology, Gaithersburg, MD, 2015).
2. C.N. Chang, B. Semma, M. Pardo, D. Fowler, P. Shamberger, and R. Arroyave. MRS Advances (2017).
3. M. Stember, The Social Science Journal 28, 1 (1991).
4. M. Nissani, The Journal of Educational Thought 29, 2 (1995).
5. M. Borrego and L.K. Newswander, The Review of Higher Education 34, 61 (2010).
6. P. Stock and R.J. Burton, Sustainability 3, 1090 (2011).
7. National Science Foundation, *Introduction to the IGERT Program*, WWW Document, (https://www.nsf.gov/crssprgm/igert/intro.jsp).
8. V.B. Mansilla, E.D. Duraisingh, C.R. Wolfe, and C. Haynes, The Journal of Higher Education 80, 334 (2009).
9. V.B. Mansilla and E.D. Duraisingh, The Journal of Higher Education 78, 215 (2007).

10. L.R. Lattuca, D. Knight, and I. Bergom. International Journal of Engineering Education 29, 3 (2013).
11. D. Fowler, R. Arroyave, J. Ross, R. Malak, and S. Banerjee. Looking Outwards from the “Central Science”: An Interdisciplinary Perspective on Graduate Education in Materials Chemistry. ACS Books, Volume tentatively titled “Educational and Outreach Projects from the Cottrell Scholars Collaborative (2017).
12. E.J. Hackett and D.R. Rhoten, Minerva 47, 407 (2009).

Appendix A. An Example of Competence Rubrics

(10) Materials Science Engineering

The student will be able to: Master concepts and principles of Materials Science Engineering.

Performance Indicators		4	3	2	1
a.	Master the process-structure-property-performance paradigm of materials science.	Use the processing-structure-property-performance paradigm as the central framework to understand materials.	Recognizes that in order to achieve specific material properties, modifications to materials structure through processing are necessary.	Aware of the existence of process-structure-property-performance relationships.	Aware of the concept of materials and materials properties
		Review			
		Strength	Gap	Recommendation	Current Level
		<Text here>	*<Text here>*	*<Text here>*	*<Text here>*
b.	Master material properties.	4	3	2	1
		Connects potential applications to material properties that must be enhanced.	Familiarity with most important material property domains: mechanical, electrical, magnetic, optical, etc.	Understands material property as the response of a material to an external stimulus	Aware of the concept of materials properties.
		Review			
		Strength	Gap	Recommendation	Current Level
		<Text here>	*<Text here>*	*<Text here>*	*<Text here>*

Note: The table is adapted from [11].

Appendix A. An Example of Competence Rubrics (Cont'd)

(10) Materials Science Engineering *The student will be able to: Master concepts and principles of Materials Science Engineering.*					
Performance Indicators		4	3	2	1
c.	Master the concept of structure in materials and materials systems as the multi-scale arrangement of matter.	Makes the inverse connection between desirable properties and the structure that is most relevant and that is amenable to modification.	Identifies relevant scale and type of structural feature that control specific properties.	Aware that materials behavior is controlled by structural features that range from electrons to the meso-scale and beyond	Aware of the concept of materials structure in the general sense.
		Review			
		Strength	Gap	Recommendation	Current Level
		<Text here>	*<Text here>*	*<Text here>*	*<Text here>*
d.	Master the concept of process-structure connections.	4	3	2	1
		Identifies different types of processing schemes that can be used to modify the multi-scale structure property of materials in order to affect specific properties.	Makes the connection between the characteristics of different processing approaches and their effect on materials structure.	Aware of the possibility to modify the multi-scale structure of materials via processing.	Aware of the concept of materials processing as any operation done on any material or material system to modify its shape and/or function.
		Review			
		Strength	Gap	Recommendation	Current Level
		<Text here>	*<Text here>*	*<Text here>*	*<Text here>*

Note: The table is adapted from [11].

Appendix A. An Example of Competence Rubrics (Cont'd)

(10) Materials Science Engineering *The student will be able to: Master concepts and principles of Materials Science Engineering.*					
Performance Indicators		4	3	2	1
e.	Master major materials classes.	From the point of view of materials development, the student realizes that what matters is property/performance, without much emphasis on a specific materials class.	Makes the connection between the general properties of a specific material class and its multi-scale structure.	Aware of the typical structural features and property ranges of the main materials classes.	Recognizes the major materials classes (ceramics, metals, polymers, etc.)
		Review			
		Strength	**Gap**	**Recommendation**	**Current Level**
		<Text here>	*<Text here>*	*<Text here>*	*<Text here>*

Note: The table is adapted from [11].