Outcomes, evidence, and learning experiences for interdisciplinary graduate engineering education

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***Abstract**: Interdisciplinary approaches are cited as critical to solving some of the most pressing technological challenges. Despite the proliferation of graduate programs designed to fill this need, there is virtually no archival literature identifying learning outcomes, methods, or benchmarks for evaluating interdisciplinary programs and associated student learning. The US National Science Foundation's Integrative Graduate Education and Research Traineeship (IGERT) program is aimed squarely at advancing interdisciplinary graduate education of scientist and engineers, and funded programs are often viewed nationally as a source of best practices. In this paper, we report on analysis of 130 proposals for funded IGERT sites. Using an instructional design framework, we focus on desired learning outcomes, evidence, and learning experiences. As US programs rely on coursework to inject interdisciplinarity into traditional disciplinary programs, the authors are particularly interested in discussing alternative models with engineering professors in other countries that rely less on coursework at the graduate level.*

Introduction and theoretical framework

Interdisciplinary approaches are necessary for attacking the most critical technological and socio-technological challenges facing the world today. Students and their training programs are recognized as central to increasing interdisciplinary research capacity (National Science Foundation, 2006). Despite the proliferation of interdisciplinary graduate programs designed to fill this need, there is virtually no archival literature identifying learning outcomes, methods or benchmarks for assessing interdisciplinary programs and associated student learning (one exception is: Richards-Kortum, Dailey, & Harris, 2003). The purpose of this analysis is to understand how academics conceptualize interdisciplinary graduate education in order to identify common practices and recommend improvements.

The theoretical framework for this analysis comes from instructional design. In *Understanding by Design,* Wiggins and McTighe (2005) describe a framework for instructional design to support student learning such that it is more focused, measurable and effective, in an effort to improve student achievement. This "backward design" framework emphasizes a process that begins with the identification of the desired results and then "works backwards" to develop teaching, training and instruction and suggests defining criteria for assessment of student learning. The three main stages are: (1) Identify desired *outcomes* and results, (2) Determine what constitutes acceptable *evidence* of competency in the outcomes and results (assessment), and (3) Plan instructional strategies and *learning experiences* that bring students to these competency levels.

The emphasis in stage one is to define the long term goals and objectives that will create "enduring understanding beyond the classroom" and discipline specific-content. Wiggins and McTighe suggest different facets of knowledge to consider when developing desired outcomes: interpret, apply, have perspective, empathize, and have self-knowledge. Readers will probably recognize that these types of action verbs are similar to Bloom's Taxonomy.

In stage two, the instructor decides in advance what evidence will demonstrate that learning outcomes have been achieved, such as comprehension and skill attainment. Wiggins and McTighe define three types of assessment evidence: performance tasks such as a real-world challenge in context, criterion referenced assessments such as quizzes and tests, and less formal unprompted assessment and self assessment such as observations and dialogues. Certainly all of these types of evidence are also present in graduate courses. However, for the research phases of graduate education, Hoey (2008) also recommends using the artefacts students already produce, including seminar presentations, research proposals, and preliminary or qualifying exam responses.

In stage three, instructors plan the learning activities and environments that will prepare students for summative assessments such as performance tasks and exams. Wiggins and McTighe emphasize the importance of closely relating all three stages to each other in a coherent, consistent manner (2005). In other words, learning outcomes should be well-defined, and all teaching and learning activities should support achievement of the learning outcomes. Applied to interdisciplinary graduate education, this framework generates three research questions, which we used to guide this analysis: (1) What *desired outcomes* are currently associated with interdisciplinary graduate education? (2) What *evidence* is currently used to assess interdisciplinary graduate education? and (3) What *learning experiences* are being designed for interdisciplinary graduate education?

To address these questions, the authors collected and analysed successful proposals (those which were approved for funding) from a long-running (1998 to 2008) interdisciplinary graduate education funding program. IGERT, the US National Science Foundation's $400 million investment in innovative graduate programs, includes in its stated purpose, "establishing innovative new models for graduate education and training in a fertile environment for collaborative research that transcends traditional disciplinary boundaries" (National Science Foundation, 2009). The results of this study indicate that many interdisciplinary graduate program proposals lack strong connections between desired outcomes, evidence, and learning experiences, and suggest that more thorough integration of each of these goals may better support new interdisciplinary programs.

Methods

This study is an analysis of 130 successfully funded IGERT proposals. In the summer of 2008, one author contacted the past and present PIs of the 195 IGERT awards with start dates from 1999-2006, using the public NSF awards site to locate awards and contact information. Ultimately, 120 of 134 proposals collected included all of the sections necessary for our analysis. They represent interdisciplinary programs inclusive of a wide range of STEM disciplines, including engineering. The proposals were formatted for use in NVivo qualitative analysis software.

Constant comparative method (Strauss & Corbin, 1998) was employed to thoroughly and systematically analyse our data and arrive at conclusions. Based on the three stages for instructional design to support student learning identified by Wiggins and McTighe (2005), we worked together to create a list of codes that would capture the most important information relating to desired outcomes, evidence and learning experiences. This process included reading the proposals, then coding segments, and re-coding and grouping codes into broad clusters of similar topics. Weekly meetings between the researchers were used to discuss the findings, structure the data for presentation, and highlight key findings. Multiple investigators contributed to the triangulation of the data (Maxwell, 1998). The overall coding structure is reflected in the headings and subheadings of the results section; however, for this brief paper, we do not include highly technical outcomes and learning experiences which are specific to the interdisciplinary domain. Quantitative measures (such as percentages of proposals that cited certain strategies) were also included, as appropriate, giving this study the benefit of a mixed-methods approach (Sandelowski, 2003).

Results

Desired outcomes

Broad perspective

The highest number of proposals described some type of perspective broadening that students would experience in the interdisciplinary program. Many (n = 64, 53%) stated that students earning degrees in one discipline would better understand the other disciplines involved in the program, e.g. "Understand and value other disciplines as they relate to their focus discipline" or a "comprehensive understanding of multiple scientific disciplines." A number of proposals (n = 36, 30%) emphasized systems thinking or integration of this knowledge from multiple disciplines. One program aspired to "Develop a curriculum that equips students to understand and integrate scientific, technical, business, societal, and ethical issues so they are prepared to take on the challenging problems of the future, including sustainability," while another will offer students "training in systems-level engineering research." In addition to disciplinary perspectives, 24% of proposals listed other perspectives we refer to as non-disciplinary, including: being "sensitive to the wider range of human diversity," having "new perspectives on social impact and viability," awareness of environmental and social responsibility and global issues, and "bridg[ing] the gap from science to policy." Only 12% of proposals employed the analogy of boundary crossing, e.g. "The ultimate products of our IGERT will be professionals who are capable of and inclined to work across interdisciplinary boundaries to solve important environmental problems." Even fewer emphasized that a problem focus would help students think outside disciplinary boundaries and access the skills and expertise necessary to solve complex problems, or that the interdisciplinary program would establish common ground between students from different disciplinary degree programs.

Teamwork

The most clearly articulated interdisciplinary learning outcome was teamwork and/or collaboration (n = 50, 42%). These were also the types of outcomes most likely to be stated as measurable learning outcomes using action verbs. For example, under a heading of "Teamwork and Professionalism," one proposal listed three specific outcomes: (1) "Understanding of group dynamics associated with leadership, membership, and peer-to-peer interactions," (2) "Ability to listen, give, and receive feedback," and (3) "Ability to set appropriate goals, milestones, and division of labor." Another proposal listed "an ability to work as a multidisciplinary team to achieve research goals." Others described students as "highly capable of collaboration" or "who are comfortable working with scientists with distinct complementary skills."

Interdisciplinary communication

Many proposals listed communication skills as an important part of professional development, but 28 of them (23%) associated the skills directly with interdisciplinarity. For example, some stated that students would be able to "communicate in a multi-disciplinary environment" or "communicate across disciplines," or that the program would develop students' "communication skills in multiple disciplines" or "the ability to effectively communicate technical concepts from their disciplines to the other [discipline]." While specific skills such as writing and presenting were also listed, interdisciplinary communication was just as often associated with collaboration and teamwork.

Interdisciplinary environment

One program goal not directly focused on students is also worth mentioning. In their broad overall goals for the program, several proposals (n = 58, 48%) listed the goal of creating an interdisciplinary environment for students. Example goals include to "Create an environment where students of diverse backgrounds engage in effective peer-learning" and creating "both physical and intellectual environments that support team building, mutual learning, and collaborative planning and decision making."

The interdisciplinary environment for learning is important for two reasons. First, because of the interactions between disciplines, interdisciplinary education lends itself well to a sociocultural perspective on learning that takes into account the environment for learning. Second, specific to this proposal analysis, it is indicative to an indirect approach to interdisciplinary education of graduate students. Particularly for proposals that did not fit into any of the categories above, focus is on the *environment* rather than the actual interdisciplinary research skills that students will gain. In other words, academic staff will work hard to develop an environment for students to take advantage of, but they may not work directly to help students navigate this space. We believe this is an underlying assumption of the proposals we analysed, and that more direct emphasis on student outcomes would help focus efforts and ensure student outcomes are met.

Evidence

The second stage of "backwards design" is evidence that the desired outcomes have been met. Each proposal contained a section on program evaluation, as required by the IGERT RFP. However, only 32% (n = 37) of the assessment sections directly mentioned evaluating how well the students learned interdisciplinary or other skills. Many of the programs' plans for assessment were based more on student numbers associated with program-level evaluation rather than student learning. Examples of these primarily quantitative measures include: student GPAs, number of minority students, number of students in attendance at activities, and student placement in academic positions. One of the proposals which did directly address student interdisciplinary skills stated "We also value students' progress in developing communication, teamwork, project management and mentoring skills." Focusing evidence on program-level measures rather than student learning is not inherently problematic; it is the mismatch between stated goals of teamwork, communication and broad perspectives and evidence that for the most part does not address student acquisition of these skills. Fortunately, many of the learning experiences are better focused on desired outcomes for student learning.

Learning experiences

As required by the IGERT RFP, each proposal included an extensive education plan. PIs were creative in designing a wide range of education, professional development and outreach activities. Terms such as "workshop," "seminar," "discussion group" and "project" were used frequently but with a variety of meanings. Thus, we coded specific items in the education plans according to the major learning outcomes identified in the previous section.

US academics rely heavily upon coursework to provide interdisciplinary learning experiences for doctoral students in traditional disciplines. The most popular strategy to achieve the learning outcomes was undoubtedly new course development (n = 98, 82%). Most of the courses would be "team-taught" by an instructor team representing various disciplines. One proposal explained, "Courses will be developed and taught by faculty members from different departments; thus, they will be interdisciplinary." In addition to new courses to be created, many proposals also required the students to take already established courses outside their home discipline. An example from one proposal is that "biologists needed to take two to three computer science courses."

Broad perspective and interdisciplinary community

Building an interdisciplinary community and/or providing students with a common base of knowledge was described in 39 of the proposals. (In this section these two outcomes are combined because most proposals described them together.) One explained:

> *These breadth courses are intended to provide a solid foundation for our students in FC [Fuel Cell] fundamentals, systems, engineering, and entrepreneurship. The integrated sequence of courses is in development and care is being taken to provide students of diverse backgrounds with the tools they will need to grasp, work with, and expand upon the material learned in class.*

The courses that were based on creating common knowledge within the interdisciplinary group were generally fundamental courses that established the basics of each of the disciplines participating in the program. The added side-effect of creating this shared knowledge is that the students then have an easier time forming a social community within the program. Additionally, 82 proposals planned extracurricular activities to build community or establish a common base of knowledge among the students. The most common extracurricular means of bringing students together was with seminars (n

= 30), which would, as one proposal promised, "develop a strong sense of community." Other frequently cited activities were program-sponsored retreats and conferences (n = 23), training workshops (n = 12) and common physical space for members of the program (n = 8).

Teamwork

Teamwork was addressed in the coursework descriptions of 45 proposals. Frequently, teamwork was to be achieved through class team projects. The purpose of one team project is described here:

> *These tasks will be performed as a group effort to promote team interaction and to develop interdisciplinary skills. The goal is to get the group of students functioning as a team, with each student playing an integral role. At the same time, it is important that the students develop an appreciation for the skills that the other members of the team bring to the collaborative effort.*

An example of one such project was for engineering and neuroscience students to "be given both the scientific question to be addressed and the experimental technique to address that question, and will be instructed to reach beyond that current technique to develop new or improved ways to measure important quantities."

Approximately the same number of proposals (n = 47) addressed teamwork outside of coursework, frequently in the context of interdisciplinary research (n = 19). One proposal describes the approach:

> *[I]t can give them [students] research experience in an area complementary to their eventual dissertation research. The goal of the project is to bring together a small, interdisciplinary team of students with diverse experience, to complete a research project that exemplifies interactive digital media, such as an interactive art installation, a digital performance, or a mobile multimedia database application.*

Other ways teams were utilized in the proposals were: seminars (speaker series with or without discussion) (n = 12), team internships (n = 9), and training workshops (n = 8).

Interdisciplinary communication

Similar experiences for building students' communication skills were described for courses and out of class components, but extracurricular requirements were listed in twice as many proposals (coursework n = 42, extracurricular n = 89). Interdisciplinary communication skills were to be built primarily through presentations, written artefacts, and informal discussions across disciplines. Proposals reasoned that these presentations, papers, and discussions would occur in the presence of all students in the program (representing various disciplines) and are therefore interdisciplinary. However, the discussion skills to be developed in informal settings were most often associated with interdisciplinarity. Seminars, for example, would afford students the opportunity "to practice communication in an interdisciplinary context" where "students from several different disciplines provide unique perspectives on selected issues." At other times, interdisciplinary discussion skills were closely aligned with other outcomes, such as common understanding enabling communication skills: "The goal... is the need to create a common language…For students to work effectively at this interface requires the ability to speak both [biology and physical science] languages and to recognize the inherent importance and origin of each mother tongue." Similarly, the few references to written interdisciplinary communication skills referred to reports of team projects. In the context of oral presentations, references to interdisciplinarity were oblique; class presentations would "force the students to synthesize their results and integrate them into a logical presentation," while seminar presentations would provide "feedback from experts in different aspects of a problem while developing articulation and presentation skills."

Conclusion

One hundred thirty successfully funded interdisciplinary graduate program proposals were analysed using a three-stage curriculum design framework. Four desired student learning outcomes were identified: contributions to the technical area, broad perspective, teamwork, and interdisciplinary communication skills. A range of types of evidence were also identified, but the most specific measures were focused at the program level (e.g., student graduation rates) rather than on student learning. Learning experiences were more closely aligned with the desired outcomes, but peculiar patterns suggest that more thorough integration may better support new and continuing interdisciplinary programs. The US academics represented in this study relied heavily on coursework to accomplish the learning objectives. Teamwork was emphasized as an outcome in 50 proposals, but only associated with research in 19. Communication skills were addressed through extracurricular requirements rather than integrated into courses and research, which are the core of graduate education. In sum, although interdisciplinary outcomes are identified from the proposals, they are not fully integrated into the core activities of graduate education. Given the technical focus of the academic staff who wrote these proposals, these findings are promising, but examination and reflection of educational processes are also important to providing the best educational experiences possible.

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Acknowledgements

The authors wish to thank the National Science Foundation for supporting this work through grant number EEC-0643107. The views expressed in this paper are those of the authors and do not necessarily represent those of the National Science Foundation. We are also grateful to IGERT PIs for sharing their successful proposals, and to Veronica Arroyave and Lynita Newswander for initial data analysis and early drafts of this paper.