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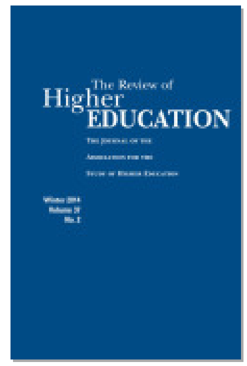

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Interdisciplinary approaches are necessary for attacking the most critical technological and socio-technological challenges facing the world today, including climate change, sustainability, energy, and public health (NIH, 2006; NSF, 2006). Graduate students and their training programs are recognized as central to increasing interdisciplinary research capacity. The strategic plan of the U.S. National Science Foundation (NSF) states: "Future generations of the U.S. science and engineering workforce will need to collaborate across national boundaries and cultural backgrounds, as well as across disciplines" (NSF, 2006, 6.

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 gradu-

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ate programs and associated student learning, particularly in science and engineering (exceptions include Anthony, Palius, Maher, & Moghe, 2007; Cowan & Gogotsi, 2004; Martin & Umberger, 2003; Richards-Kortum, Dailey, & Harris, 2003). Among the recommendations for future interdisciplinary graduate education published in a recent NSF report is the desire to "develop specific outcome goals for skills development in the broad topic of professional skills and match training to these goals" (Van Hartesveldt & Giordan, 2009, p. 4). Developing operational definitions of interdisciplinarity through learning outcomes is an important first step to developing and assessing the effectiveness of interdisciplinary graduate programs. A number of authors note that, while engineering and science faculty have little difficulty writing learning outcomes for technical work, the domains of teamwork, graduate education, and interdisciplinarity are challenging in their own rights and usually lie well beyond the background or experience of most technical faculty members (Boix Mansilla & Dawes Duraisingh, 2007; Felder & Brent, 2003; Hoey, 2008; Klein, 2008).

While it is not the norm in science and engineering for faculty to study or publish on interdisciplinary research processes, there is a wealth of informative literature in the field of interdisciplinary studies in the humanities. Scholars such as Julie Thompson Klein (1990, 1996, 2008), William Newell (Klein & Newell, 1998), Veronica Boix Mansilla (2006; Boix Mansilla & Dawes Duraisingh, 2007), Rainer Bromme (2000), and Lisa Lattuca (2001) study, reflect, and write about interdisciplinarity, describing in detail the intellectual processes of combining and resolving disciplinary perspectives to advance knowledge and understanding. The very disciplinary silos and discourse communities that stand as barriers to interdisciplinary research and education also serve as barriers to combining and transferring this scholarship in ways that would be informative to sciences, engineering, humanities, and social sciences alike.

The purpose of our analysis is to combine practical knowledge from engineering and science faculty with peer-reviewed literature from interdisciplinary studies in the humanities to advance understanding and make constructive suggestions for the outcomes of interdisciplinary graduate education. The research questions which guided this analysis are: (a) How do science and engineering faculty implicitly or explicitly define interdisciplinary research for the purposes of graduate education? (b) And how can the interdisciplinary literature from humanities guide the articulation of desired learning outcomes for interdisciplinary graduate education?

Since the literature specific to interdisciplinary learning in science and engineering is sparse, we collected empirical data in the form of 129 successful proposals to the U.S. National Science Foundation's Integrative Graduate Education and Research Traineeship (IGERT) program. Since 1998 this program's purpose of "establishing innovative new models for graduate education and training in a fertile environment for collaborative research that transcends traditional disciplinary boundaries" (NSF, 2009, p. 4) has earned it a reputation as the premier source of innovation in interdisciplinary science and engineering graduate education in the United States, particularly across a range of institutions. The major learning outcomes emerging from qualitative analysis of these proposals were compared to the literature from the humanities for additional insight. This comparison, utilizing the most appropriate sources from each discipline, highlights important overlaps, intersections, and omissions which illuminate interdisciplinarity in the sciences, engineering, humanities, and social sciences.

BACKGROUND AND LITERATURE REVIEW

Defining Interdisciplinarity, Multidisciplinarity, and Transdisciplinarity

Noted interdisciplinarian Julie Thompson Klein (1990) offers a general and oft-cited definition of interdisciplinarity: "Interdisciplinarity is a means of solving problems and answering questions that cannot be satisfactorily addressed using single methods or approaches" (p. 196). To those who distinguish multidisciplinarity from interdisciplinarity, multidisciplinarity is less integrative, often a temporary or weak combination of contributions from multiple disciplines (Berger, 1972; Chubin, Porter, Rossini, & Connolly, 1986; Committee on Facilitating Interdisciplinary Research, 2004). While earlier definitions of transdisciplinarity focused on overarching theories that transcended traditional disciplines (Berger, 1972; Lattuca, 2001), the term has more recently taken on a meaning that includes a broader range of stakeholders, including practitioners and the public in its focus on solving authentic problems (Gibbons, Limoges, Nowotny, Schwartzman, Scott, & Trow, 1994; Klein, 2005).

However, many academics who practice some type of research that crosses or combines disciplines do not draw these distinctions. For the purposes of this article, we will use the most common term, "interdisciplinary," to refer collectively to activities that may, strictly speaking, be multidisciplinary, interdisciplinary, or transdisciplinary. One of the major aims of this analysis is to understand what science and engineering faculty mean when they describe interdisciplinary graduate education and its variants. Thus, we will use the literature and data from the proposals to develop an understanding of what is meant, desired, and desirable in interdisciplinary graduate education in science and engineering. We note that, since the purpose of graduate education is to prepare the next generation of scholars, the faculty proposal writers in this study do not appear to distinguish between descriptions of their own interdisciplinary research experience and their goals for their students.

Science and Engineering Operationalizations of Interdisciplinarity

Team-based collaboration is the norm in engineering and science: "In the experimental sciences, collaboration is more likely to involve a division of labor. If a scientist confronts a problem which requires skills [he or she] does not possess, [he or she] must seek to involve others in it" (Hagstrom, 1964, p. 244). High consensus and well-defined terminology in science and engineering fields enable a division of labor (Lodahl & Gordon, 1972). For example, specific types of instrument-based analyses can be requested, performed, and reported with limited discussion or interaction among team members. In contrast, there is less frequent but closer collaboration in lower-consensus social science and humanities disciplines because they require that researchers work more closely to agree on methods and interpretations (Lodahl & Gordon, 1972). As a result, collaboration—as measured by multi-author publications—occurs more frequently in technical fields (Bayer & Smart, 1991; Beaver & Rosen, 1979; Biglan, 1973). It is only natural, then, that, as science and engineering tackle more and more interdisciplinary problems, they are primarily approached by collaborative teams. Our results section demonstrates that science and engineering IGERT principal investigators (PIs) do indeed appear to operationalize interdisciplinarity as teamwork.

Several interdisciplinary studies scholars define interdisciplinarity in terms of collaboration between individuals representing traditional academic disciplines. Repko (2008) explains:

> Interdisciplinarity is often a collaborative process. . . . An expert interdisciplinarian is one who is able to integrate the input of others to address an issue, which may include coordinating team members. This trait applies especially to interdisciplinarians engaged in technical and scientific studies that most commonly involve teamwork. (p. 44)

Similarly, Bruhn (2000) defines interdisciplinary research as "two or more persons from different disciplines who agree to study a problem of mutual concern, and who design, implement, and bring to a consensus the results of a systematic investigation of that problem" (p. 58). Others define this type of team-based interdisciplinarity as one of a few types of interdisciplinarity. Rhoten and Pfirman (2006) define team-collaboration (one of four mechanisms) as "multiple researchers with mastery in their distinct fields or disciplines, working collectively as a network or team of individuals to trade and exchange tools, concepts, ideas, data, methods, or results around a common project" (p. 58). While these humanities and social science scholars acknowledge the pervasiveness of teams in interdisciplinary settings, much of their literature does not focus on interpersonal interactions or processes.

One notable exception is an emergent social science field, the "science of team science," which seeks to

> study the organizational and institutional factors which cause cross-disciplinary, multi-institution scientific and engineering research initiatives to succeed or fail. It grew out of evaluation of government and private sector investments in research centers and the like. (Stokols, Hall, Taylor, & Moser, 2008, p. S78)

Social science studies of large interdisciplinary team endeavors, including those situated in policy and evaluation, are informative about interdisciplinary research literature and constitute an important means of addressing macro-level team aspects of interdisciplinarity, but they are not as directly relevant to this analysis.

While the division of labor characteristic of science and engineering is highly efficient, it has also been criticized in the literature on interdisciplinarity for limiting integration across disciplines (Committee on Facilitating Interdisciplinary Research, 2004; Klein, 1990; Rhoten, 2003). While scholars like Repko acknowledge the need particularly for scientific and engineering interdisciplinarians to cultivate collaboration skills, much of the interdisciplinary studies literature focuses on the individual intellectual processes of synthesizing perspectives, theories, and methods from multiple disciplines. It is this literature that informs a deep definition of interdisciplinarity, which in turn fleshes out key learning outcomes. As readers will see, there are important parallels between these humanities-based descriptions of interdisciplinary integration and implicit graduate learning outcomes hinted at by science and engineering faculty. Taken together, they demonstrate an unexpected transferability of interdisciplinary integration processes and provide important depth and focus to science and engineering interdisciplinary learning outcomes.

Humanities Conceptualizations of Interdisciplinary Scholarship

Much of the literature on interdisciplinarity focuses on typologies (such as the definitions presented above) that critique pseudo-interdisciplinary efforts which are not truly integrated (e.g., Lattuca, 2001) or focuses on the evaluation of interdisciplinary products and artifacts (e.g., Boix Mansilla & Dawes Duraisingh, 2007). While these works are important in conceptualizing and defining interdisciplinarity, they are less illuminating about processes of interdisciplinary integration that would lead to specific, measurable learning outcomes. Repko's *Interdisciplinary Research* (2008) summarizes key scholars (including those cited above) but is organized into chapters representing steps in the interdisciplinary research process: (a) identifying relevant disciplines, (b) developing adequacy in relevant disciplines, (c) analyzing the problem and evaluating each insight into it, (d) identifying conflicts in insights, (e) creating (or discovering) common ground, and (f) integrating insights and producing an interdisciplinary understanding. The issue is further complicated by a combination of affective and cognitive qualities that are not easily separated; attitudes such as broad interest in and respect for the contributions of other disciplines appear to be preconditions for interdisciplinary learning and scholarship (Ivanitskaya, Clark, Montgomery, & Primeau, 2002; Repko, 2008; Richter & Paretti, 2009).

Focused more on summative evaluation than process, Veronica Boix Mansilla and Elisabeth Dawes Duraisingh (2007; Boix Mansilla, Dawes Duraisingh, Wolfe, & Haynes, 2009) interviewed faculty in interdisciplinary undergraduate programs and developed three criteria for assessing interdisciplinary work: (a) disciplinary grounding, (b) integrative quality, and (c) critical awareness. We combined these two lists and related literature to identify four important themes relevant to interdisciplinary process and evaluation. They include the three identified by Boix Mansilla and Duraisingh (and reflected in Repko's list) but highlight the process of resolving conflicts between disciplines and creating common ground (combining Repko's 4 and 5 into one additional theme). Each of these four is described in the subsections which follow.

Disciplinary Grounding. Boix Mansilla and Dawes Duraisingh (2007) define disciplinary grounding as "the degree to which student work is *grounded* in carefully selected and adequately employed disciplinary insights" (p. 222; emphasis theirs). The measure is divided into the selection of appropriate disciplines and application consistent with "disciplinary theories, findings, examples, methods, validation criteria, genres, and forms of communication" (p. 222). In evaluating student work, faculty should also consider whether any key disciplinary perspectives are missing and ensure that the work does not exhibit any misconceptions (Boix Mansilla & Dawes Duraisingh, 2007).

Boix Mansilla and Dawes Duraisingh (2007) reported that faculty experts felt that students did not need to master each of the contributing disciplines but that they did need enough depth to reflect on the nature of disciplines and make meaningful connections. Similarly, Repko (2008) cites a willingness to achieve "adequacy" in multiple disciplines as an important distinguishing quality of an interdisciplinarian, and Borrego, Newswander, and McNair (2007) emphasize disciplinary grounding for engineering students in interdisciplinary learning environments (2007).

Some of the faculty interviewed criticized the power and privilege of disciplines in higher education (Boix Mansilla & Dawes Duraisingh, 2007). This power derives in part from the alignment of higher education resources and rewards with traditional disciplines, leading to perceived career risk among junior researchers (Rhoten & Parker, 2004). In response to these perceptions, the IGERT program under study also emphasizes "deep knowledge in chosen disciplines" by stating that "students should gain the breadth of skills, strengths, and understanding to work in an interdisciplinary environment while being well grounded with depth of knowledge in a major field" (NSF, 2009, p. 4). In this case, it appears that one traditional discipline is still preferred over the tradeoff that learning multiple disciplines might force. This preference reflects a tendency of positivists to accept disciplines as natural or logical constraints to be worked around with limited reflection on epistemology (Lattuca, 2001).

Integration. Boix Mansilla and Dawes Duraisingh (2007) also emphasize the integration of disciplinary insights to advance knowledge or understanding. Integration consists of "articulating the cognitive advantage enabled by the combination of perspectives. . . . It entails characterizing the specific ways in which the whole of the understanding is more than the sum of its disciplinary parts" (pp. 227–228). They point to evidence such as "conceptual frameworks, graphic representations, models, metaphors, complex explanations, or solutions that result in more complex, effective, empirically grounded, or comprehensive accounts or products" (p. 222). Integration lies at the heart of interdisciplinarity, and variations are present in most discussions of interdisciplinary learning outcomes. Ivanitskaya, Clark, Montgomery, and Primeau (2002) cite Field, Lee, and Field (1994) for identifying the ability to synthesize or integrate, Ackerman and Perkins (1989) for the ability to devise connections between seemingly dissimilar contexts, and Ackerman (1989) for the ability to generate analogies and metaphors. Borrego et al. (2009) argue for integration as a primary interdisciplinary skill for engineering undergraduate students. Repko (2008) lists the ability to think dialectically to resolve conflict and spends several chapters describing in detail, with examples, how to identify conflicts between disciplinary insights, create or discover common ground among the insights, and finally integrate them to produce a new interdisciplinary understanding.

Communication and Translation across Disciplinary Boundaries. While integration is by nature dialectic, we separate it from communication across disciplinary boundaries to highlight a separate but overlapping body of literature explicitly addressing interpersonal communication. Language and terminology differences between disciplines are perhaps the most frequently cited barrier to interdisciplinarity (Brewer, 1999; Fry, 2001; Gooch, 2005; Repko, 2008; Salter & Hearn, 1996). Citing Lattuca, Klein, Bradbeer, and Boix Mansilla, Gunilla Oberg (2009) directly links interdisciplinary communication to the concept of common ground: "Successful interdisciplinary research groups invest considerable time in managing differences and creating common ground. Clearly, those able to create a climate that stimulates dialogue within the group have a greater chance of success" (p. 407). Common ground is a concept from psychology used to describe communication between individuals. Olson and Olson (2000) define the term:

> Effective communication between people requires that the communicative exchange take place with respect to some level of common ground (Clark, 1996). *Common ground* refers to that knowledge that the participants have in

> common, and they are aware that they have it in common. (p. 157; emphasis theirs)

Common ground is established most efficiently through face-to-face conversation aided by verbal and nonverbal cues. Oberg (2009) notes that scholars from similar disciplines sometimes overestimate the level of common ground, which can make interdisciplinary collaboration counterintuitively more challenging than when the differences between disciplines are obvious. Olson and Olson (2000) similarly note, "Joint construction of common ground can be an especially taxing form of interaction, especially when people appear to be similar but have important hidden dissimilarities" (p. 158). Nonetheless, Repko (2008) quotes others who state that common ground is "essential" and "fundamental" to interdisciplinary research (pp. 275–276).

Oberg (2009) does not define common ground directly but describes the problems of judging the quality of interdisciplinary work when differing disciplinary criteria are applied. This observation implies that the common ground she seeks is agreement on what constitutes quality demarcation, cited literature, methodology, analysis methods, reliability, reflexivity, and standards for presentation of the results:

> Differing perceptions of quality and credibility among disciplines are major obstacles to successful collaboration. . . . Hence, when involved in activities that span traditional scholarly borders, you need not only to become familiar with the procedures of your own discipline, but also to acquire consciousness of and respect for variations among research procedures. (p. 406)

While these statements echo disciplinary grounding, the article goes on to describe a guided discussion to help collaborators build consensus regarding evaluation criteria. While interdisciplinary studies have begun to borrow from psychology to understand interpersonal communication, the extensive literature on teams remains largely untapped for understanding interdisciplinarity. Many of the analyses cited above are based on individual student papers and other artifacts, which, like humanities and social sciences, are not as focused on teamwork as engineering and science (Bayer & Smart, 1991; Beaver & Rosen, 1979; Biglan, 1973). Also as noted above, a number of humanities and social science researchers, particularly those studying faculty and professional interdisciplinary researchers, define interdisciplinary research as a collaborative endeavor (Bruhn, 2000; Repko, 2008; Rhoten & Pfirman, 2006). Thus, Repko's (2008) exhaustive list of attitudes and skills includes references to collaboration and communication with others, but his description of interdisciplinary processes tends to deemphasize collaborative processes.

Critical Awareness. Another key aspect of interdisciplinary education as described in literature from the humanities addresses the way that an individual understands and makes sense of various types of knowledge. A general awareness that "truth" and "knowledge" in any discipline are susceptible to influence by social factors (such as funding, resources, and biases of the researchers themselves) is often referred to simply as "critical awareness." According to Boix Mansilla and Dawes Duraisingh (2007), critical awareness allows an individual to competently assess the "degree to which [a given] work exhibits a clear sense of purpose, reflectiveness, and self-critique" (p. 222). In addition, this questioning attitude helps to facilitate "framing problems in ways that invite interdisciplinary approaches and exhibiting awareness of distinct disciplinary contributions, how the overall integration 'works,' and the limitations of the integration." Simply stated, critical awareness is not only an attitude for learning but also a method for analyzing the benefits, challenges, and shortcomings of one's own research. As such, it is a useful strategy for traditional disciplinary work as well as for interdisciplinary work (Ivanitskaya et al., 2002; Repko, 2008).

As a method of analysis, critical awareness produces certain benefits to interdisciplinary work, including an added clarity of purpose and a reflective understanding of "the choices, opportunities, compromises, and limitations that characterize interdisciplinary work and the limitations of the work as a whole" (Boix Mansilla & Dawes Duraisingh, 2007, pp. 228–229). It allows researchers to use their judgment to weigh options and reason through various aspects of a problem. Additionally, it helps to eliminate bias by making a researcher consciously aware of any barriers to objectivity, and therefore keeps the researcher humble (constantly aware of possible shortcomings) while at the same time empowering him or her (Ivanitskaya et al., 2002). Values of creativity, flexibility, and the ability to generate analogies and metaphors—which are also attributed to critical awareness (Dunbar, 1997; Ivanitskaya et al., 2002; Spiro, Vispoel, Schmitz, Samarapungavan, & Boerger, 1987)—are especially important to interdisciplinary work (e.g., Borrego & Newswander, 2008; Borrego, Newswander, & McNair, 2007).

An added benefit of critical awareness as a mode of research or analysis is its emphasis on holistic thinking—looking at the bigger picture, valuing outside perspectives, and enlarging possible horizons of knowledge (Ivanitskaya et al., 2002; Repko, 2008). It is worth noting that Repko's (2008) and Ivanitskaya et al.'s (2002) literature reviews of interdisciplinary learning outcomes also describe a number of attitude changes, such as humility, tolerance for ambiguity, and enlarged perspectives. The empirical data will reinforce the relevance of these outcomes for engineering and science graduate students.

Methods

Setting

The Integrative Graduate Education and Research Traineeship (IGERT) program is the flagship funding program for the U.S. National Science Foundation's Division of Graduate Education. Having funded more than 4,800 graduate students from more than 195 grants at 98 institutions since 1998 (Brown & Giordan, 2008; Van Hartesveldt & Giordan, 2009), it is widely regarded as a premier source of innovation in interdisciplinary graduate education in the United States, particularly across a range of institutions. The request for proposals (NSF, 2009) describes IGERT's interdisciplinary focus:

> The program is intended to catalyze a cultural change in graduate education, for students, faculty, and institutions, by establishing innovative new models for graduate education and training in a fertile environment for collaborative research that transcends traditional disciplinary boundaries. . . . Students should gain the breadth of skills, strengths, and understanding to work in an interdisciplinary environment while being well grounded with depth of knowledge in a major field. (p. 4)

In addition to interdisciplinarity, the IGERT program addresses a range of goals for graduate education in science and engineering. The report credited with motivating IGERT cites issues such as: Ph.D.s who are underprepared for work in nonacademic settings, concerns over lack of diversity of graduate-level scientists and engineers, and the need for professional development in areas such as ethics (Committee on Science Engineering and Public Policy [COSEPUP], 1995). The most recent IGERT request for proposals (RFP) also emphasizes that funded sites should prepare graduates "to understand and integrate scientific, technical, business, social, ethical, policy and global issues to confront the challenging problems of the future" (NSF, 2009, p. 4). In other words, the proposals we analyzed focused on meeting a variety of goals, and the interdisciplinary aspects on which we focus may or may not reflect the overall quality of the proposals. Nonetheless, due in large part to a lack of archival literature and empirical studies on the subject, these proposals reflect vanguard thinking on interdisciplinary graduate education in science and engineering.

Data Sources

For this broad survey across a large number of programs, we elected to analyze successful proposals for three important reasons. First, because the program began in 1998 and grants regularly run as long as five or six years, there are many more successful proposals than final reports in existence. Second, the format for final project reports focuses on program-level assessment and management and does not necessarily capture all that faculty have learned about interdisciplinary learning outcomes from the experience (Hrycyshyn, 2008). Third, faculty members have developed a culture of sharing successful large proposals with others, and these were likely to have included as (or more) detailed descriptions than we could have collected in surveys.

In the summer of 2008, the first 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, 134 responded by submitting all or part of their proposals for our review. Four of the proposals were incomplete, so we did not analyze them as part of this study. We formatted the remaining 130 proposals for use in NVivo qualitative analysis software and together created a list of codes that would capture the most important information relating to learning outcomes. By carefully reading several proposals, we determined that most of this information could be found in the "Vision, Goals and Thematic Basis," "Education and Training," and "Performance Assessment/Project Evaluation" sections of the proposals (required by the RFP). Only one of the 130 respondents had failed to include all three sections in the documents they provided. The final dataset also includes 12 renewal proposals for the same program (i.e., 117 unique programs were represented).

Disciplines across a wide spectrum are represented in these interdisciplinary proposals. All NSF Directorates allocate funding to the program, representing biological sciences, computer science, education, engineering, geosciences, mathematical and physical sciences, and social, behavioral, and economic sciences. IGERT categorizes the grants according to 14 themes including sustainability, computational science and engineering, human and social dimensions of new knowledge and technology, nanoscience, energy, materials, bioinformatics, civil infrastructure, entrepreneurialism, neuroscience, climate change, biological evolution and development, diverse device development and sensing, and signals, imaging, and signal processing (Brown & Giordan, 2008). As proposals represent the collaborative effort of as many as 20 faculty members, categorizing them by discipline is virtually impossible.

Data Analysis

We performed content analyses (Leedy & Ormrod, 2004) on the textual data using primarily qualitative methods, but the dataset was large enough that we also included quantitative measures as appropriate (such as percentages of proposals that cited certain outcomes), giving this study the benefit of a mixed-methods approach (Sandelsowski, 2003). We employed a constant comparative method (Strauss & Corbin, 1998) to create codes, organize the data, compare findings to each other and to the literature, and to reorganize the data as necessary. First, we extracted all statements related to graduate student qualities or learning outcomes. We then coded those most directly related to transferable interdisciplinary student learning outcomes into the four categories corresponding to the subsections of our results: (a) grounding in traditional disciplines, (b) integration and broad perspective, (c) teamwork, and (d) interdisciplinary communication. Although there are important overlaps and connections among these four, we developed distinct categories that reflect the descriptions embedded in the proposals in ways that can extend or be extended by the literature. For example, although Boix Mansilla and Duraisingh (2007) separate integration and critical awareness, the data were simply not descriptive or deep enough to subdivide in this way. Additionally, teamwork emerged from the data as perhaps the most clearly articulated outcome for science and engineering students, even though it is not emphasized in the humanities literature. Three additional categories emerged, which we do not discuss further: highly technical outcomes with limited transferability (e.g., "students will become leaders in nanotechnology" or learn to use a specific piece of equipment), program-level outcomes (e.g., student graduation rates), and descriptions of the interdisciplinary environment to which students would be exposed.

RESULTS

Grounding in Multiple Traditional Disciplines

Half of the proposals (n = 59 sites, 50%) described various ways graduate students would develop knowledge and awareness of multiple traditional disciplines in order to conduct interdisciplinary research. Several proposals enumerated the disciplines required to conduct quality research in the interdisciplinary area, with varying levels of specificity as to students' desired level of proficiency: "We propose a graduate training program in which all participating students are exposed to physical, economic, policy, and journalistic aspects of carbon and climate." "Each student will gain core knowledge in atmospheric sciences, engineering, economics, and related areas of mathematics." "Students must demonstrate basic competence in mathematics, molecular genetics, computer science, and statistics." "[S]tudents can work comfortably in all three fields (biology, physical science, and engineering)."

Other proposals more clearly specified which aspects of the various disciplines would be the focus of graduate training, such as "models, methods, and results of scholars in adjacent fields," "the material and the language and approach of different traditional disciplines," and "appropriate literature, methodologies, principles, and vocabulary necessary to integrate the relevant perspectives." These were some of the broadest statements, and we note that others emphasized, for example, particular analysis methods that bridged traditional disciplines in the specific interdisciplinary domain.

Presumably the ultimate purpose of this grounding in multiple disciplines is to solve important interdisciplinary research problems. Various proposals stated that students would learn how to "approach problems from multiple vantage points," to "appreciate and apply advances from disparate disciplines," and be "sufficiently conversant with other fields to conduct significant, cutting edge interdisciplinary research." These statements are similar to a recent report on the IGERT program: "To carry out interdisciplinary research, one must have both disciplinary capability and interdisciplinary conversance" (Van Hartesveldt & Giordan, 2009, p. 2). One proposal passage explains the logic particularly well:

> It is not feasible to expect tomorrow's scientists to have expertise in *both* social and aquatic systems, but what is feasible is to create an appreciation of the intellectual challenges faced by the respective disciplines, the methodology used to pursue these challenges, and the ability to formulate and solve interdisciplinary problems effectively.

Only one proposal stressed reflection on the limitations of disciplines as emphasized in the literature (Boix Mansilla & Dawes Duraisingh, 2007), listing three relevant learning outcomes: "(1) Appreciate and understand methods used in other disciplines, (2) Understand and value other disciplines as they relate to their focus discipline, and (3) Understand methodological limitations within their own as well as other disciplines."

Several proposals were also careful to emphasize primary grounding in one traditional discipline (which reflects language in the IGERT RFP). A few motivated this grounding in the belief that good interdisciplinary team members represent a traditional discipline well. However, it was much more common to cite the job market as the reason. One proposal combined both explanations:

> Our goal is to train scientists who are well-trained in one or more disciplines but have an understanding and research experience in a range of natural and social sciences. We feel that students must be well grounded in a particular discipline to provide them with a depth of expertise that they can bring to an interdisciplinary research effort. In addition, they must have strong disciplinary tools and experience that give them the necessary credentials to obtain jobs and get tenure in today's academic environment.

Other statements about the job market included: "Students must start with a strong disciplinary/departmental base to assure rigorous theoretical and methodological foundations and to create clear avenues within the job market," and "[I]f anything, the students in this program must have a stronger than average training in economics to overcome prejudice in the profession regarding multidisciplinary Ph.D. programs."

Some sites, by nature of their interdisciplinary domain, emphasized as few as two disciplines in which all students would develop competency, while others spanned a wider range of disciplines. At least some proposals were careful to limit the number of disciplines an individual student would learn as necessary for research on the specific dissertation topic.

Integration Skills and Broad Perspective of the Interdisciplinary Domain

To integrate across disciplines, students need a broad view of the problem and the contributions of various perspectives to that problem. Nearly one-third of the proposals (n = 36, 30%) emphasized some sort of systems thinking or integration of this knowledge from multiple disciplines.

Some proposals emphasized the broad view that students would develop: "While each student cannot perform research that deals with each of these aspects, by participating in this coherent program, he/she will be able to see how each project provides information needed to understand the whole." Another proposal explained, "We seek to train a generation of graduate students who understand the linkages among all of these aspects of [domain]." Others explained that this broad perspective would translate into integrative research:

> Our goal is to produce Ph.D.s with the better-rounded skills needed to assess and formulate workable solutions to environmental problems. . . . The frequency and duration of interactions across disciplines in environmental studies is not yet sufficient to inculcate the interdisciplinary outlook needed to reliably identify the key problems for scientific and policy purposes, and then to stimulate creative solutions to those problems.

Many proposals emphasized "integrative thinking," "synthesis of knowledge," "the ability to integrate knowledge from different disciplines to solve specific research problems," and to address the complexity of the interdisciplinary research domain. One proposal sought to "develop an integrative skill set in a diverse group of graduate student trainees that will enhance their abilities to contribute to the solution of complex interdisciplinary problems." To achieve this goal, faculty relied on new courses "focusing on integration of perspectives" and, to a lesser extent, dissertation research:

> Advising must be structured with disciplinary integration as a specific goal, not something that miraculously appears at the end. IGERT PhD committees will be composed of faculty members from different disciplines who have major interests in integration. Academic programs of study and dissertation projects will have multi-disciplinary components.

In addition to disciplinary perspectives, 24% of proposals listed other perspectives, 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." Similarly, among important elements of transformative interdisciplinary graduate education, an NSF report lists

> training that leads students to work comfortably, independently, and effectively at interfaces, i.e., not only having the knowledge of how interdisciplinary teams

> could be put together and how to work with people in other fields, but also how to develop research vision and carry out the research at interdisciplinary interfaces (Van Hartesveldt & Giordan, 2009, p. 15).

Teamwork

The most clearly articulated interdisciplinary learning outcome was teamwork and/or collaboration (n = 48 sites, 41%). In many cases, faculty investigators equated interdisciplinary research with teamwork. One proposal quoted directly from a cited source, "We agree with [authors] that 'interdisciplinary research is most likely a team effort.'" Others emphasized the additional capabilities of teams over individual researchers, explaining that their students "will see firsthand that a multidisciplinary team that approaches difficult issues from a range of perspectives can make exciting advances that no single group of investigators could accomplish." Most proposals simply listed teamwork and/or collaboration in passing with little description of what that entails, but a few gave in-depth explanations, such as:

> Multi-disciplinary research means different things to different people. In our experience, most successful multi-disciplinary research takes place collaboratively, in small or large teams consisting of scholars with strong backgrounds in traditional disciplines, but with interest and knowledge in other fields that complement each other well to solve problems in information technology, content, or systems. Such researchers may or may not be sufficiently qualified on their own to undertake and publish original research in a field outside of their original discipline, but they are able to communicate with researchers from other disciplines, and to work collaboratively, creatively, and productively together. We have designed the [IGERT] program on this vision: [D]octoral students will receive strong traditional disciplinary education and a degree from a traditional department, but will work with students and faculty from other disciplines throughout their doctoral program, and take courses in other fields, in order to learn how to collaborate and jointly produce multidisciplinary solutions to important problems.

Some emphasized a focus on interdisciplinary teamwork because it is the reality of the careers for which they are preparing students. One proposal pointed out, "In addition to traditional expectations of a deep understanding of a relatively narrow technical area and proven ability to undertake significant independent research, Ph.D. graduates are increasingly required to work in multidisciplinary, and often geographically distributed, teams." Another motivated its focus on teaming by explaining that graduate students "will work together in collaborative multidisciplinary teams to understand disciplinary viewpoints, just as faculty members or industrial/government counterparts do when working on interdisciplinary projects."

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: (a) "Understanding of group dynamics associated with leadership, membership, and peer-to-peer interactions," (b) "Ability to listen, give, and receive feedback," and (c) "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 as a desired outcome students who would be "highly capable of collaboration" or "who are comfortable working with scientists with distinct complementary skills." It was clear that faculty were cultivating in students the transferable skills to work on different teams in the future. One very important skill explicitly identified was the ability to communicate with others.

Interdisciplinary Communication

In addition to interdisciplinary research skills, IGERT also has the goals of diversity, ethics, and professional development. As part of professional development, many proposals emphasized oral and written communication skills. We were careful in our analysis to code only learning outcomes that the faculty investigators themselves directly related to interdisciplinarity. Thus, we report that 28 sites (24%) describe interdisciplinary communication as a goal or outcome, but many more than this describe communication in general.

Many of the proposals included vague references to communication skills across disciplinary boundaries, e.g., students would "acquire language skills to move comfortably across disciplinary boundaries." Fewer specified which audiences would be targeted. A small number emphasized researchers and collaborators specifically. For example students would learn "how to communicate with their collaborators" at one site, perhaps through "[f]requent and effective communication between research team members" at another site. A third site explained, "We want our students to be capable of communicating their research to scientists who are not specialists in their particular field."

More common among specific statements of the audience for interdisciplinary communication was both science and nonscience audiences. One listed as a desired outcome that students would be able to "communicate effectively, in writing and orally, with both subject area experts and the layperson." Another stated the goal of improving "students' ability to communicate technical challenges, ideas, and results to diverse audiences . . . particularly to nonspecialist audiences." A third explained, "We will develop in our IGERT fellows the crucial communication skills they will need for them to effectively engage in science and policy issues with researchers, policy experts, industry, the media, the lay public, and their own future students."

Within communication, we coded interdisciplinary statements related to "communication," "language," and "fluency." Based on some of the statements, we believe that "fluent" and "language" may simply be metaphors for disciplinary grounding described above:

> As disciplinary language is often a barrier to collaboration and understanding, Fellows will learn to "speak one another's languages" by studying the approaches, methods, terminology, and questions of other disciplines from the very beginning of their graduate education in the IGERT program.

Other scholars have noted that, while language and terminology differences among disciplines are perhaps the most frequently cited barrier to interdisciplinarity, they often signal differences that are deeper and more conceptual (Brew, 2008; Gooch, 2005; Repko, 2008). Similarly, we note that 14 proposals included only vague statements that students would cross disciplinary boundaries; however, such boundaries could not be clearly defined or categorized based on the immediate context of the statements.

Again, many of these sentiments are echoed in NSF reports, specifically the link between teamwork and communication:

> Teamwork skills are a necessity for all graduate students regardless of their graduate programs. Teamwork skills include the critical ability to communicate across disciplines, and teamwork training can take place either as part of coursework or during work on a research project. . . . The ability to communicate the value and importance of science to public stakeholders is also becoming more important. Therefore, effective interdisciplinary training must also include mechanisms of effective communication to nonscientific as well as scientific audiences outside a given area of expertise. (Van Hartesveldt & Giordan, 2009, p. 15)

Discussion

Disciplinary grounding was an important value emphasized in both the humanities literature and the engineering and science proposals. Only the proposals, however, were concerned with the perceived tradeoffs of breadth and depth. This pattern could be attributed to their focus on graduate education, which is already plagued with concerns about time to graduation (Nettles & Millett, 2006) and closely aligned with perceived career risks of interdisciplinarity to untenured faculty (Rhoten & Parker, 2004). It could also, to some extent, be attributed to positivists' tendency to view disciplinary boundaries as natural and logical rather than socially constructed, arbitrary power structures (Lattuca, 2001; Salter & Hearn, 1996). In other words, science and engineering faculty may view disciplines and traditional faculty reward structures more as constraints or barriers than as fair game for scholarly criticism.

Establishing common ground was presented in the literature and the proposals as important for communication. (Otherwise, what is the value of knowledge advancement through interdisciplinarity?) The proposals tended to stress that common ground was to be established through students' common experience in coursework, seminars, and other program components designed to build interdisciplinary community. To a surprising extent, establishing common ground was faculty driven rather than presented as a transferable skill for students to develop. This dynamic is somewhat understandable, as students are being trained in a particular interdisciplinary domain with a fairly static, defined set of relevant disciplines with which to familiarize themselves. Similarly, the decision of which disciplines are relevant to the domain was made in advance by the faculty who were designing the program. In order to make it a transferable skill, the process Oberg (2009) proposed might be followed to prepare students to facilitate discussions of expectations with new collaborators.

Integrating appropriate disciplinary perspectives toward increased understanding is a common theme of interdisciplinarity, across disciplinary perspectives. However, we might argue that humanists operationalize integration as critical awareness, while engineers and scientists operationalize it as teamwork. Both the literature and the proposals achieve thick descriptions of integration through other related concepts rather than detailed definitions of integration. The humanities literature describes considering disciplinary perspectives, identifying inconsistencies and limitations, resolving these in some way, and reflecting on this process. The proposals point to a perceived reality that engineering and science research is conducted in teams regardless of the employment sector. They then go on to describe disciplinary grounding, the need for a broad perspective to understand how disciplinary contributions might fit together, and the communication skills necessary to collaborate in support of team science. It is clear from the results that these faculty view ideal interdisciplinarians as well-grounded representatives of their own traditional discipline who can also conceptualize how other disciplines might contribute to a problem and collaborate with others representing traditional disciplines. Seeing the big picture and the ability to establish interdisciplinary teams was associated with leadership in some of the proposals.

Critical awareness is the outcome around which humanities scholarship can most extend engineering and science conceptions of interdisciplinarity. While engineering and science faculty members avoid criticism of disciplinary structures, they would certainly say they value graduate students' critical thinking about the problem at hand and the value of various disciplinary approaches to it. Critical awareness requires reflecting on epistemology and respecting different ways of knowing as a means to, as only one proposal articulated, "(1) Appreciate and understand methods used in other disciplines, (2) Understand and value other disciplines as they relate to their focus discipline, and (3) Understand methodological limitations within their own as well as other disciplines." The ability to access various disciplinary perspectives has been related to creativity and creative problem-solving through analogies (Dunbar, 1997; Ivanitskaya et al., 2002; Spiro et al., 1987). Repko (2008) and Ivanitskaya et al. both argue that interdisciplinary skills are important to all students because they develop independent, critical thinking and creativity:

> With repeated exposure to interdisciplinary thought, learners develop more advanced epistemological beliefs, enhanced critical thinking ability and metacognitive skills, and an understanding of the relations among perspectives derived from different disciplines. (Ivanitskaya et al., 2002, p. 95)

While we have found that IGERT PIs tend to provide various levels of engagement with interdisciplinarity and match students to these levels rather than forcing anyone to be more interdisciplinary than they are comfortable with (Newswander & Borrego, 2009), the rhetoric of interdisciplinarity as a way to promote creativity is beginning to enter into NSF IGERT discourse:

> It has been observed that students attracted to interdisciplinary graduate education appear to be more independent and more likely to "think outside the box" than others. On the other hand, it has also been observed that interdisciplinary graduate training enables students to tackle more complex research problems, to be more creative, and to take greater risks. (Van Hartesveldt & Giordan, 2009, p. 4)

Thus, there is support for increased critical awareness in interdisciplinary graduate education in engineering and science. As Boix Mansilla and Duraisingh (2007) explain, it is not enough to simply integrate disciplinary perspectives well; skilled interdisciplinarians explicitly reflect on the challenges and processes of integration, including the limitations of various disciplinary perspectives and the synergistic value of the interdisciplinary approach. Explicit discussions of epistemology would therefore have value in advancing the creativity of engineering and science graduate students, particularly in interdisciplinary research domains.

What, if anything, can humanities learn from science and engineering descriptions of interdisciplinarity? The dialectic nature of humanities requires scholars to "speak" to other disciplines, even if primarily in writing. We might argue, however, that in an increasingly globalized and interconnected world, few people work in complete isolation. Recent generations of college-age students are more interested in making a difference and solving complex problems (e.g., poverty, social justice) that will call for increasingly transdisciplinary approaches, working in concert with stakeholders as well as academics from a variety of disciplines. Perhaps the team projects emphasized in engineering curricula (as well as solutions for facilitating and grading joint work) could be transferred to humanities and social science classrooms and graduate programs to cultivate a complementary set of interdisciplinary integration skills to the writing currently emphasized.

SUMMARY

Comparing the interdisciplinary studies (humanities) literature with a content analysis of 129 successful proposals (written primarily by science and engineering faculty), we identified and discussed five categories of learning outcomes for interdisciplinary graduate education: (a) disciplinary grounding, (b) integration, (c) teamwork, (d) communication, and (e) critical awareness. Both sources valued disciplinary grounding, communication and establishing common ground, and the integration of disciplinary perspectives. However, humanities literature operationalized integration through critical awareness, while engineering and science proposals operationalized it as teamwork. In other words, humanities emphasized (solitary) intellectual skills, whereas science and engineering emphasized interpersonal skills. Nonetheless, there were important complements and parallels between the two approaches. Specifically, critical awareness extends engineering and science definitions of critical thinking and creative problem solving. Team projects were suggested as a means of developing complementary integration skills in humanities students. Applying the lens of interdisciplinary studies (humanities) to science and engineering provides important depth and focus to engineering and science interdisciplinary learning outcomes (particularly in detailing integration processes), while science and engineering experience with teams represents a potential resource for education in the humanities.

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