Integrative Graduate Education and Research

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Abstract

Driven both by the increasing pace of scientific discovery and the development of new technologies, strategies for graduate education are emerging to prepare students for collaborative work across disciplines. Outstanding graduate students are attracted to research problems of relevance to important social goals and are capable of combining disciplinary depth with interdisciplinary breadth without prolonged time to degree, as shown by the National Science Foundation's Integrative Graduate Education and Research Traineeship (IGERT) program. Programs that intentionally prepare graduate students for interdisciplinary work typically include an interdisciplinary curriculum with participation of faculty from several different areas to help students learn the language and culture of another discipline and structured settings in which students learn to collaborate across disciplines and work in teams to solve research problems. Activities beyond the classroom help students to negotiate disciplinary divides in other ways. The departmental/disciplinary organization of most universities is a challenge for both students and faculty seeking disciplinary flexibility in education. To encourage a new ecosystem supporting interdisciplinary education and

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research, universities are creating new organizational policies to provide both the flexibility and the rewards and incentives for faculty to work and educate across disciplines. Funding agencies are adapting their own organizational structures to find new ways to accommodate interdisciplinary research and education.

Introduction

The increasing pace of scientific discovery and the development of new technologies have stimulated new strategies for interdisciplinary research and education. While there are many terms that have been used to describe research across the disciplines, including multidisciplinary, transdisciplinary, convergent (Stokols 2014), and even postdisciplinary, the term "interdisciplinary" as defined by the National Academies (CFIR 2004) will be used in this chapter to represent all collaborative approaches to research and education across the disciplines. The National Academies' definition is as follows: "Interdisciplinary research (IDR) is a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice" (CFIR 2004, 2). As disciplines themselves evolve, what is defined as interdisciplinary changes over time, as researchers borrow the techniques and expertise of fields outside their own to solve new research problems. Interdisciplinary research has led to new disciplinary fields, such as neuroscience, nanoscience, and bioinformatics, for example. Thus, topics that are considered "interdisciplinary" now may be considered "disciplinary" in the future.

A doctorate in the science, technology, engineering, and mathematics (STEM) disciplines is a research-intensive degree, during which students learn both the conceptual and technical aspects of conducting research in a particular field to create new knowledge. The traditional model for disciplinary education is the "apprenticeship" model with a research advisor, undertaken in a department where disciplinary depth is acquired. The doctoral student is expected to work as an individual to produce an original scientific investigation of a research problem, traditionally within a discipline, which serves as the dissertation. However, as the scope of the scientific research needed to solve important problems broadens, graduate students increasingly need the skills to create new knowledge in topics that cross disciplines. The kind of education to be discussed here is interdisciplinary doctoral education that *intentionally* prepares graduate students to work across multiple disciplines and become capable of conducting interdisciplinary research, rather than providing circumstances in which students may *incidentally* acquire these skills. The opportunities and challenges for interdisciplinary doctoral education for students, and the roles in this area for faculty, universities, and federal funding agencies, will be the topic of this chapter.

Numerous calls for reforms in graduate education (Wendler et al. 2012; NRC 2012) have included recommendations that graduate students get more academic breadth (COSEPUP 1995; CFIR 2004). Four studies published after the COSEPUP report had similar recommendations, including encouraging interdisciplinary work in graduate school (Carney et al. 2006). Still other reports have strongly recommended that graduate education have an interdisciplinary component (CFIR 2004; Derrick et al. 2012; ACS 2013; Murday et al. 2013), in order to foster the pursuit of creative research as well as to build career skills.

The National Science Foundation made awards in its Integrating Graduate Education and Research Traineeship (IGERT) program from 1998 to 2013; IGERT was the only federally sponsored training program that intentionally fostered doctoral education with an interdisciplinary theme across all the STEM disciplines. Called "America's hallmark grant program for interdisciplinary training" (Gamse et al. 2013, 8), IGERT has been the subject of considerable examination and evaluation, and thus examples and findings for this program provide much of the substance for this chapter.

Each IGERT project had at its heart an interdisciplinary theme chosen by its faculty, who designed a graduate education program to prepare students to carry out collaborative research on topics related to the theme. Examples of interdisciplinary theme categories include nanoscience, sustainability, clean energy, sensors, and human and social dimensions of new knowledge and technology, to name a few (Brown and Giordan 2008). Many of these forward-looking themes are related to the interdependence of the natural and human systems as well as vision-inspired research, two of the principles of convergence (Roco et al. 2013). IGERT had many other goals including professional development for students, increasing diversity, global engagement, and changing the culture of graduate education at the institution. As it evolved, IGERT added innovation as another important skill for students to develop so that the interdisciplinary research they conduct might be used for the benefit of society, in the spirit of convergence.

IGERT: A Model for Interdisciplinary Graduate Education

Interdisciplinary graduate education programs can be designed in many ways, depending upon the goals of the program. Faculty fashion their programs to give students the interdisciplinary skills and experiences they think most appropriate for the interdisciplinary research to be done. IGERT faculty created a variety of programs, all of which offered students a curriculum and activities designed to provide them with both the personal and professional skills to carry out interdisciplinary collaborations. In spite of the wide variety of interdisciplinary themes in IGERT programs, there was considerable consistency in the kinds of activities that were incorporated into the projects. In almost every IGERT project, faculty designed interdisciplinary courses intended to help bridge the disciplines involved in the project. These courses were challenging for faculty to design and for students to negotiate. Creating a graduate-level introduction to multiple disciplines so that the

course was neither too difficult nor too easy was both an exciting and a trying experience for faculty, and one that raised many issues. Sometimes prerequisite courses were recommended, raising issues both of the suitability of an out-of-discipline course for a graduate student (imagine a biology student taking an undergraduate engineering course) and whether the student would get graduate credit for an undergraduate course in a field outside his or her discipline. Students were concerned about their lack of background for that part of the curriculum that was in new disciplines for them (Hrycyshn 2008). Notwithstanding the considerable effort that went into the initial design of interdisciplinary courses, most IGERT faculty revised them after the first time they were offered. Those projects that empowered graduate students to help design or redesign and implement the interdisciplinary curriculum got a double benefit: the faculty members were relieved of some of their workload, and the graduate students (who knew firsthand what was needed) were energized by taking ownership of their education. Even though interdisciplinary courses were demanding for both faculty and students, both thought that these courses were an important part of interdisciplinary preparation for graduate students (Gamse et al. 2013).

In addition to interdisciplinary courses, most IGERT projects have used team research projects to prepare their students for research on topics within the project's interdisciplinary theme. Team research projects generally took place early in graduate student training. These projects were seen as useful in helping students to apply multidisciplinary approaches in a research setting, as well as offering a setting for students to learn to communicate their research to those in other disciplines (Gamse et al. 2013). Team research projects carried out in nonacademic internships focused on solving real-world problems with colleagues from different disciplines and backgrounds and helped to build career skills and networks. The value of interdisciplinary team research in the graduate curriculum has been recognized outside the IGERT program. The ACS report (2013) stated that critical skills in graduate education include communicating complex topics to various audiences, learning new science and technology after academic training, collaborating on global teams, managing projects, and understanding the ethical conduct of research. According to the ACS, "The most all-encompassing approach to these needs is to significantly enhance interdisciplinary collaboration among the students" (ACS 2013, 12). However, there remains a tension between the perceived need for graduate students to become highly independent researchers, especially in academia, and the need for them to learn how to work on research in teams (Gamse et al. 2013).

Other informal mechanisms that IGERT projects employed to better enable students to work with those outside their own disciplines were summer "boot camps" with hands-on activities, winter sessions, informal science cafes, shared office space, open laboratories and shared lab space, lab rotations, interdisciplinary laboratory and field experiences, and attendance at a professional conference outside their home discipline. IGERT projects have differed in their training mechanisms in part because IGERT faculty have interpreted the challenges of educating in an interdisciplinary theme in a variety of ways, including educating

students to become experts in more than one field, to have mastery of one field and being able to work with researchers in another, and/or to know and use the techniques of multiple disciplines (Carney et al. 2006).

Another common element of IGERT projects and other interdisciplinary graduate education programs is cross-mentoring, or student mentoring by faculty outside their home department. Cross-mentoring is another way for students to learn the language and culture of another discipline outside the classroom. IGERT participants often commented on the importance of learning the language of other disciplines, as have others (CFIR 2004). Some in IGERT reported that it could take up to a year to learn each other's disciplinary language, and to learn that the same words could mean different things in different fields. Communicating across disciplines was an important key to success, although it could be frustrating. Beyond learning a new language, students and faculty also learned the differences in each other's "cultures," including how research questions are posed, the way courses are taught, and the milestones for graduate student progress in a field outside their own.

One measure of confidence and preparation in disciplines outside the home department is the interdisciplinary nature of the topic of the dissertation. IGERT students reported using more disciplines than non-IGERT students in their dissertations (Carney et al. 2011). It is informative to compare dissertation outcomes of IGERT students with those of the graduate students educated at NSF's Science and Technology Centers (STCs), which are Centers that are directed at large, complex, and frequently interdisciplinary research problems and that also include education as a part of their missions. IGERT students responded that they drew on at least two disciplines in their dissertation research far more than STC students (Martinez et al. 2011).

In addition to interdisciplinary skills, all IGERT projects emphasized the need for disciplinary depth. With few exceptions (Murday et al. 2013), there is general agreement that graduate students should develop depth in a discipline whether or not their program includes interdisciplinary training (Derrick et al. 2012; ACS 2013). Disciplinary depth gives students a recognized expertise to bring to an interdisciplinary research problem, as well as a disciplinary home if they seek a career in academia. Skeptics wondered whether it would be possible for graduate students to acquire sufficient disciplinary depth while also being involved in activities to build interdisciplinary breadth. However, both IGERT faculty and students have reported that IGERT students were as well prepared to know their own discipline in depth as non-IGERT students in the same field. While acquiring both disciplinary depth and interdisciplinary breadth, as well as transferrable skills, IGERT students completed their doctoral degrees in slightly less time on average than comparable non-IGERT students (Carney et al. 2011). Nonetheless, the question of the appropriate balance between depth and breadth continues to be an important issue in doctoral education in general and interdisciplinary graduate education in particular.

Interdisciplinary research themes are attractive to both undergraduate and graduate students (CFIR 2004). Three quarters of both IGERT and non-IGERT doctoral students reported having been drawn to an interdisciplinary graduate

education (Carney et al. 2006). A higher percentage of IGERT students found interdisciplinary graduate education to be of interest, and in that regard they could be considered a "different breed" of graduate student (Carney et al. 2011, 76). A percentage of IGERT students were attracted to the institution they attended because of the IGERT program. Many of the IGERT projects featured research on the kinds of societally relevant broad, complex real-world problems that require expertise in more than one traditional discipline. These kinds of research problems and the education to address them both inside and outside academia may appeal to more diverse students than those who have applied to graduate school to study a single discipline (Derrick et al. 2012). IGERT diversity was reported as roughly equivalent to the national averages for the disciplines represented in IGERT (Carney et al. 2011), although when data were analyzed by race, ethnicity, and gender and compared with national data by field of study, IGERT projects' diversity overall was either equal to or exceeded the relevant national data in well over half of all fields (Brown and Giordan 2008).

IGERT interdisciplinary themes were not only attractive to prospective graduate students, they were attractive to excellent prospective students. IGERT students were consistently considered better qualified than non-IGERT students by faculty (Carney et al. 2006; Brown and Giordan 2008), even though neither the IGERT students' GRE scores nor grade point averages were higher than those from comparable single-discipline graduate students. However, IGERT faculty perceived that IGERT students were more independent, more creative, more willing to take risks, more highly motivated, and better focused than single-discipline graduate students (Van Hartesveldt and Giordan 2009).

The risks inherent in a nontraditional degree program may be attractive to some students but not to others. Prospective students must be confident that they can meet all the requirements of a nontraditional degree, attain the degree, and succeed in obtaining the kind of employment that they value. Much of the perception of risk results from the fact that graduate education is highly oriented toward and controlled by departments that represent single disciplines. Departments traditionally recruit and admit graduate students, assign them research advisors, set the requirements for graduation, and allocate departmental resources such as teaching assistantships and travel funds. In addition to these departmental assets and actions, departments also help their students to establish a sense of professional identity and intentionally or unintentionally promote a career path to a faculty position. The disciplinary emphasis within departments is reinforced by the fact that individual departments are often associated with professional societies. Students pursuing an interdisciplinary program may lack a clear sense of professional identity, and their interdisciplinary program may not give them as strong a support group as a disciplinary/departmental program. A career path to a faculty position, if that is what is desired, may not appear as clear. In addition, students pursuing an interdisciplinary option may not be seen as worthy of departmental funding, since they (or their advisors) may not be viewed as "belonging" sufficiently to the departmental discipline, and they may not be

given teaching assistantships if it is thought that they do not have sufficient content knowledge within the discipline to be effective. In summary, the university's organizational structure, particularly at the level of the department, is a force to be reckoned with for anyone trying to operate outside its domain. It is not surprising that faculty saw graduate students willing to work outside the confines of a department as a "different breed."

An interdisciplinary graduate education can be judged as successful only if it prepares its graduates for desirable careers. On average about half of all doctoral degree holders will be working outside academia (Wendler et al. 2012), with the percentage varying according to field of degree. For graduates who will work outside academia, an interdisciplinary graduate education provides many of the skills that employers value, including the ability to work in teams, the ability to apply knowledge in one area to solve problems in another area, and good communication skills, among others (Wendler et al. 2012). When student career expectations are limited to tenure-track faculty positions in a single-discipline department, in spite of the decreasing availability of these positions (Golde and Dore 2001), then student success may depend upon departmental valuation of publications in particular journals or research on disciplinary topics. However, academia is changing, albeit slowly. Cluster hiring is being used at some universities to build interdisciplinary faculty teams focused on broad, complex research questions. This is one way that the university can establish a focus on particular areas of interdisciplinary research in areas of national priority with likely federal funding. Examples of universities currently engaged in substantial cluster hiring include North Carolina State University, the University of Florida, and Notre Dame University.

To what extent were IGERT students successful in obtaining employment, and to what extent has their interdisciplinary training carried through into their careers? IGERT graduates have reported having little difficulty in finding employment, and most thought that their IGERT training had given them a competitive edge (Carney et al. 2011). The area of their education considered of highest value by IGERT graduates was their interdisciplinary training, followed by communication skills and professional networks. In spite of broader training and opportunities for internships outside academia, the degree to which IGERT students worked in the various employment sectors is about the same as that of non-IGERT graduates (Carney et al. 2011). About half of IGERT graduates surveyed continued to draw upon the disciplines they used in their dissertations in their careers, and about half were using new fields; the latter suggests that IGERT students developed the transferrable skills to become involved with new disciplines. IGERT graduates with positions in academia have been very active in supervising interdisciplinary student research projects, establishing interdisciplinary courses, and creating interdisciplinary programs of study (Carney et al. 2011). Thus the IGERT program not only affected the institutions where the graduate students were trained but also the educational institutions where they found employment. The multiplier effect of IGERT graduates on higher education is a powerful force for change.

Interdisciplinary Graduate Education: Organizational Challenges

Both interdisciplinary research and education are driven by the faculty, who conduct the research and develop and teach the curricula. Doing exciting new research and providing students with an effective education for the future have their own incentives and rewards, including attracting adventurous, outstanding students who want to be working on the cutting edge of important research and the opportunity to do new research and have new avenues for funding, and to work with new collaborators. However, these incentives and rewards cannot substitute for measures of faculty success within the organizational hierarchy of the university. Many have recognized that the university must work to remove barriers and provide incentives and rewards to the faculty who take on research and education outside the auspices of their department (e.g., CFIR 2004). When faculty initiate and carry out interdisciplinary graduate education programs, they will likely be developing cross-departmental curricula, team-teaching interdisciplinary courses, participating in informal activities to build rapport and community among faculty and students, and mentoring and serving on dissertation committees of students outside their home departments. If the faculty's interdisciplinary activities are added on to a full disciplinary assignment, they may suffer from overload. In addition, evaluation of the quality of teaching and curricular development is difficult; evaluation of the quality of interdisciplinary courses and informal activities is even more difficult but essential if interdisciplinary education is to thrive. The work that faculty do outside the department may not be fully appreciated inside the department, and may even be considered a detriment, particularly when tenure and promotion are considered.

The academic department is the traditional home of the faculty, responsible for faculty recruitment and appointments, space and teaching assignments, tenure, promotion, and raises. Departments are also typically the locus of graduate student admissions and decisions regarding assignments of teaching assistantships, the second largest source of external support for graduate students (NSB 2014). Thus, the attitude toward interdisciplinary research and education in the department where a faculty member has his or her appointment is critical for one planning to work across departments. Faculty with appointments in traditional departments assigned to teach disciplinary undergraduate courses may find a tension between their disciplinary and interdisciplinary identities. If they do not teach disciplinary undergraduate courses, their graduate students may not be appointed on teaching assistantships. Faculty members need clear consistent messages from university administrators from the top down to every hierarchical level, including that of the department, outlining their assignments. They may also need help from their administrators in developing research and education programs across colleges and departments (Van Hartesveldt and Giordan 2009).

It has been said "the traditional academic departments at universities and colleges are…discouraging interdisciplinary collaboration…" (Murday et al. 2013, 252) and that the "basic organizational structure of most higher education institutions is all but incompatible with interdisciplinary education and research" (Borrego et al. 2014, 337). One American university, Arizona State

University, has reorganized its structure in order to promote interdisciplinary collaboration (Crow and Dabars 2014). Abroad, Seoul National University has formed the Graduate School of Convergence Science and Technology, in which separate academic departments are loosely divided into four programs (Murday et al. 2013). Much as in IGERT, in each program all students take an introductory course in subjects that cross disciplinary boundaries and participate in a project that is carried out by teams of students from different academic backgrounds. However, in the U.S.A., most universities continue to work within their disciplinary organizational frameworks to overcome their barriers to interdisciplinary research and education in order to attract top faculty and outstanding graduate students.

Creative ways that universities may give graduate students more academic flexibility begin at the time of admissions. In the ACCESS program at UCLA, graduate students may be admitted to graduate study in an interdisciplinary field, then select their home department and research group later; at the University of Florida, students may also be admitted to an interdisciplinary program and decide on their department later. Arizona State University gives students multiple admission options including both traditional and interdisciplinary doctoral programs (Van Hartesveldt and Giordan 2009).

At some universities, graduate students are admitted through traditional departments but then may choose a program that gives them greater breadth. While some interdisciplinary programs become free-standing doctoral programs, creative university administrators have established a variety of mechanisms for students to gain interdisciplinary breadth and the credentials to recognize it, each tailored to that university's unique mission, organizational structure, and culture. Introductory courses may be shared across departments. A matrix design for interdepartmental interactions is employed at Michigan State University, the University of Minnesota, and the University of Idaho. Some of the new credentials that are offered and examples of the institutions that offer them include a Designated Emphasis (University of California-Davis), a dual-title degree program (Pennsylvania State University), Interdepartmental Degree Programs (University of Michigan), the Student-Initiated Degree Program (University of Michigan), and the Interdisciplinary Ph.D. program (University of Maine). Certificates, minors, and specializations or concentrations have also been used as credentials that attest to a student's breadth (Van Hartesveldt and Giordan 2009).

Universities stimulate interdisciplinary research and graduate education by establishing interdisciplinary centers and institutes and by building teams ready to tackle problems requiring interdisciplinary expertise by gathering together interested faculty or by cluster hiring. Some interdisciplinary cluster hires or centers naturally evolve into interdisciplinary departments, which may establish their own graduate programs. Interdisciplinary centers and institutes set the stage for incidental interdisciplinary graduate education but are not sufficient per se for intentional interdisciplinary graduate education. One interesting outcome of cluster hiring to build collaborative research groups is that it may include faculty from industry, who can provide graduate students with valuable teamwork and collaboration skills, along with information about careers outside academia that graduate students may

not get elsewhere. Typically, graduate students get their career advice from the faculty, who primarily encourage them to prepare for faculty positions (Wendler et al. 2012).

Roles of the Federal Funding Agencies in Interdisciplinary Graduate Education

The federal funding agencies have played an important role in stimulating interdisciplinary graduate education for the past 50 years. For example, the National Institute of Mental Health used interdisciplinary training grants in what is now behavioral neuroscience to stimulate the growth of that field long before neuroscience became a discipline. As discussed above, the IGERT program was established at NSF in 1998. In 2005, the Howard Hughes Medical Institute-National Institute of Biomedical Imaging and Bioengineering established the HHMI-NIBIB Interfaces Initiative to stimulate interdisciplinary training for graduate students in the biomedical sciences and to have a broader impact on graduate education in the institutions that were granted the awards. Each of these programs has influenced interdisciplinary research and education both for the students trained in them and at the institutions of higher education where they were located.

While it is difficult to tease out the effects of training programs such as IGERT on universities from other simultaneous influences on research and education, at least one study has indicated that on campuses with multiple IGERT awards, IGERT has affected attitudes and practices (Borrego et al. 2014). IGERT has been given credit for raising awareness of interdisciplinary research and education on campuses and thus stimulating the first step in institutional change. Programs like IGERT have had an effect on university policies on faculty hiring, workload, promotion, and tenure (Borrego et al. 2014). Policy changes that have taken place at universities with multiple IGERTs include changes in listings of interdisciplinary courses, eligibility of advisors to serve on dissertation committees outside their departments, faculty credit for cross-mentoring, and coauthored doctoral dissertation chapters.

Federal agencies not only influence graduate education by funding training grants but also by funding fellowships and research assistantships. Each of these funding mechanisms has its place in graduate education, and the mix of these mechanisms has both intentional and unintentional consequences for graduate education. Traineeship programs like IGERT and the HHMI-NIBIB Interfaces Initiative condition their funding on educational and institutional innovations in interdisciplinary education. Some fellowship programs require particular curricula or offer students internships or other special training to broaden their research and career perspectives. However, research assistantships typically lack educational requirements or goals for the education of those holding them, beyond what students learn in the course of working on the research project on the grant to

which they are appointed. About 70 % of graduate students supported by federal funds are supported on assistantships on research grants, while only about 10 % are supported on fellowships, about 10 % on traineeships, and the rest by other mechanisms (NSB 2014). Decades ago it was lamented that STEM graduate education seems to be a "by-product" of the nation's research policies (COSEPUP 1995). One unintentional consequence of the significant amount of funding for research assistantships is that it could reinforce the single-discipline, apprenticeship model of education. It has been suggested that if the federal funding agencies are to have a significant influence on the quality of graduate education through their awards, then the mix of funding for training grants, fellowships, and research assistantships should be better balanced (COSEPUP 1995; Biomedical Research Workforce Working Group 2012; ACS 2013; NRC 2012). Another way to increase the influence of federal funding on graduate education would be to incorporate educational goals for graduate students in research assistantships. For example, an individual development plan (ACS 2013) could be required for every graduate research assistant appointed on a research grant, just as it is for every postdoc appointed on an NSF or NIH award.

The current balance for funding mechanisms for graduate students affects not only the quality or type of education but also the quantity of doctoral degrees earned in a field. While fellowships and traineeships have defined programs and defined budgets that control the numbers of supported students, there is no such control on research assistantships – these are determined independently, one grant at a time. Because research assistantships are such an important source of funding for STEM graduate students, the numbers of research grants awarded and the numbers of research assistantships funded on those grants greatly influence the number of doctoral students trained in a field, and thus the number of degree holders seeking employment. The Biomedical Research Workforce Working Group (2012) found that the number of holders of the doctorate in the biomedical sciences is greater than the employment opportunities for them and has recommended that NIH shift its graduate student funding allocation from predominantly research assistantships to fellowships and traineeships, without an overall increase in numbers. The recommendation is controversial because graduate students are so intricately involved in the biomedical sciences research enterprise.

Like the organization of the traditional university, those federal funding agencies that support basic research in the STEM disciplines are organized around disciplinary topics, including the structure of the organizational hierarchy, the budget process, and the review processes. NSF is an example of an agency that faces the same challenges as the traditional university regarding the promotion of research and education across disciplinary boundaries. Strong leadership from the top is usually needed to establish programs that cross NSF's directorates. In the past, bold new initiatives to solve important societal problems could garner additional funding, giving NSF leaders a strong incentive to collaborate. In a fairly flat-funding environment, these incentives may be fewer if funds for interdisciplinary research and education programs subtract from disciplinary budgets.

Federal funding agencies like NSF thus mirror universities in their disciplinary hierarchies and allocation of funding through organizational structures organized around disciplines. Because universities depend substantially on federal funding, changing the culture of graduate education must be accompanied by, and can only be achieved by, changing the cultures of funding agencies. Funding agencies that support basic science currently have a traditional disciplinary structure over which transitory interdisciplinary initiatives are overlaid. Many of the challenges in promoting interdisciplinary research and education at federal funding agencies reflect the challenges found in academia, including the policies underlying the funding allocations, "ownership" of the venture, and the influence of important constituents or stakeholders. Because the federal funding agencies primarily fund research, graduate students are not considered as their primary focus, and graduate education is expected to take place outside the purview of the research grant. However, interdisciplinary graduate education cannot be taken for granted. It must be intentional, so that the graduate students of today will become the adventurous, creative next generation of scientists and engineers that will solve the complex research problems of tomorrow.

Closing Comments

Graduate education is influenced by many interlocking factors including the organization of the institution where they study, faculty members and their rewards and incentives, and the federal agencies that fund graduate students. Together these factors constitute the ecosystem for graduate education, and each has a critical role to play. The value of interdisciplinary research in solving large-scale problems is well recognized in industry, but universities and funding agencies lag behind in implementing the changes in policies that would support it. The value of preparing graduate students to carry out interdisciplinary research lags even further behind. Yet clearly interdisciplinary graduate education drives new interdisciplinary research, drives institutional change, and drives the future of research and education where interdisciplinary degree holders go. Interdisciplinary graduate education is one force that can help to drive convergence ecosystems to the next level.

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References

American Chemical Society Presidential Commission (2013) Advancing graduate education in the chemical sciences. American Chemical Society, Washington, DC. Retrieved from http://www.acs.org/content/dam/acsorg/about/governance/acs-presidential-graduate-education-commission-full-report.pdf

Biomedical Research Workforce Working Group (2012) Biomedical Research Workforce Working Group Draft Report. National Institutes of Health, Bethesda. Retrieved from http://acd.od.nih.gov/bmw_report.pdf

Borrego M, Boden D, Pietracola D, Stoel CF, Boone D, Ramasubramanian MK (2014) Institutionalizing interdisciplinary graduate education. In: O'Rourke M, Crowley S, Eigenbrode SD, Wulfhorst JD (eds) Enhancing communication & collaboration in interdisciplinary research. Sage, Los Angeles, pp 335–355

Brown S, Giordan J (2008) Integrative Graduate Education and Research Traineeship (IGERT): 2006–2007 annual report. National Science Foundation, Arlington. Retrieved from www.nsf.gov/pubs/2008/nsf0840/index.jsp

Carney J, Chawla D, Wiley A, Young D (2006) Evaluation of the initial impacts of the National Science Foundation's Integrative Graduate Education and Research Traineeship Program. Abt Associates, Bethesda. Retrieved from www.nsf.gov/pubs/2006/nsf0617/index.jsp

Carney J, Martinez A, Dreier J, Neishi K, Parsad A (2011) Evaluation of the National Science Foundation's Integrative Graduate Education and Research Traineeship Program (IGERT): follow-up study of IGERT graduates final report. Abt Associates, Bethesda. Retrieved from http://www.igert.org/system/content_item_assets/files/1535/ES_IGERT_FOLLOWUP_STUDY_FULLREPORT_May_2011.pdf?1340382040

Committee on Facilitating Interdisciplinary Research (2004) Facilitating interdisciplinary research. National Academies Press, Washington, DC

Committee on Science, Engineering, and Public Policy (COSEPUP) (1995) Reshaping the graduate education of scientists and engineers. The National Academies Press, Washington, DC

Crow MM, Dabars WB (2014) Interdisciplinarity as a design problem. In: O'Rourke M, Crowley S, Eigenbrode SD, Wulfhorst JD (eds) Enhancing communication & collaboration in interdisciplinary research. Sage, Los Angeles, pp 294–322

Derrick E, Falk-Krzesinski HJ, Roberts M (2012) Facilitating interdisciplinary research and education: a practical guide. AAAS, Washington, DC. http://www.aaas.org/report/facilitating-interdisciplinary-research-and-education-practical-guide

Gamse BC, Espinosa LL, Radha R (2013) Essential competencies for interdisciplinary graduate training in IGERT. Abt Associates, Bethesda. Retrieved from http://www.abtassociates.com/Reports/2013/Essential-Competencies-for-Interdisciplinary-Gradu.aspx

Golde CM, Dore TM (2001) At cross purposes: what the experiences of today's doctoral students reveal about doctoral education. Report prepared for the Pew Charitable Trusts, Philadelphia. Retrieved from http://www.phd-survey.org/report%20final.pdf

Hrycyshn G (2008) Challenges to implementation and how they were overcome: 2006–2007 IGERT annual report. National Science Foundation, Arlington

Martinez A, Shlager C, de la Cruz RJ, McGarry N, Parsad A (2011) Graduates of NSF's Science and Technology Centers: Integrative Partnership (STC) and Integrative Graduate Education and Research Training (IGERT) programs. Abt Associates, Bethesda

Murday J, Bell L, Heath J, Kong CH, Chang R, Fonash S, Baba M (2013) Implications: people and physical infrastructure. In: Roco MC et al (eds) Convergence of knowledge, technology, and society: beyond convergence of nano-bio-info-cognitive technologies. Springer, Dordrecht/Heidelberg/New York/London, pp 249–310

National Research Council (2012) Research universities and the future of America: ten breakthrough actions vital to our nation's prosperity and security. The National Academies Press, Washington, DC

National Science Board (2014) Science and engineering indicators 2014. National Science Foundation (NSB 14–01), Arlington

Roco MC, Bainbridge WS, Tonn B, Whitesides G (2013) Convergence of knowledge, technology, and society: beyond convergence of nano-bio-info-cognitive technologies. Retrospective and outlook. Springer, Dordrecht/Heidelberg/New York/London

Stokols D (2014) Training the next generation of transdisciplinarians. In: O'Rourke M, Crowley S, Eigenbrode SD, Wulfhorst JD (eds) Enhancing communication & collaboration in interdisciplinary research. Sage, Los Angeles, pp 56–81

Van Hartesveldt C, Giordan J (2009) Impact of transformative interdisciplinary research and graduate education on academic institutions. National Science Foundation, Arlington. Retrieved from http://www.nsf.gov/pubs/2009/nsf0933/index.jsp

Wendler C, Bridgeman B, Markle R, Cline F, Bell N, McAlister P, Kent J (2012) Pathways through graduate school and into careers. Educational Testing Service, Princeton