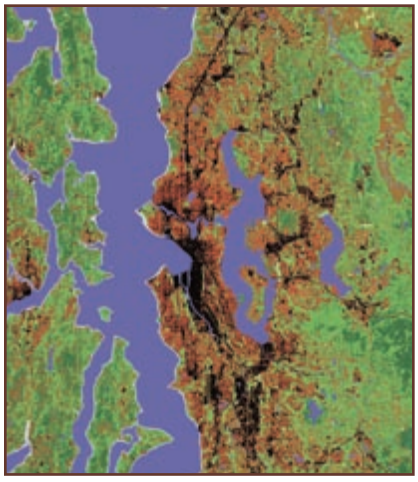
Summary of Workshop Proceedings

The workshop participants were faculty and administrative leaders from some of America's most prominent universities engaged in interdisciplinary transformation. Both the faculty and administrative leaders who participated are involved with the implications of interdisciplinary education, training, and research on a regular basis. These implications affect the way that research is conducted; how students are trained and educated; how faculty are hired, promoted, and rewarded; and even the structure of the university itself.

All invited participants in the workshop were active participants in the working groups and all were later invited to comment on the text of the report as summarized here. The Summary of Workshop Proceedings is presented in the four sections that follow. This summary is a synopsis and not a complete account of all discussions and written materials. Statements and observations shared by the various working groups that help to illustrate key points are shown throughout the text of the report.



Interdisciplinary research can lead to major practical advances and most 'problem-oriented' research is interdisciplinary.

Research Working Group, Administrators

The Impact of Interdisciplinarity on Research

Research that cuts across disciplinary lines has become increasingly prominent and important, both in basic and applied areas, concomitant with changes in technology and the increasing urgency of complex problems with societal impact. Discoveries and new technologies continue to change the way we think about problems in science and engineering and how to approach them. Both basic and applied interdisciplinary research are expected to become more important segments of the research venture in the future as issues and problems such as those relating to the biosphere, the impacts of technology on society, and renewable energy become more prominent.

Despite the need for and the value of interdisciplinary research, rigorous disciplinary research also has intrinsic value and provides the foundation for interdisciplinary

problem-oriented approaches to address new problems of large scope. Interdisciplinary research has had important impacts on disciplines in two ways.

- First, paradigms within single disciplines have often changed and benefited from researchers borrowing from and working with researchers from other disciplines. Responding to new discoveries and challenges, disciplines have advanced by utilizing theoretical, experimental, and technological advances from other fields (e.g., biological science has been advanced by discoveries in physical sciences and mathematics; archaeology benefits from new knowledge in climatology, botany, geology, etc).
- Second, many current disciplines have grown out of interdisciplinary research; examples include cognitive psychology, genomics, bioinformatics, neuroscience, and nanoscience.

Interestingly, the structure of many funding agencies, like the structure of universities, is still based on disciplines, as are the major resource allocations. These structures face the same administrative challenges that the universities do, and are encouraged to consider being leaders in terms of structural change.

Research Working Group, IGERT Principal Investigators

Interdisciplinary research may have substantial economic and societal benefit to the U.S. It has the potential to maintain U.S. competitiveness in high-value industries both through inventions and through innovations, including those that decrease the cost and increase the speed of many processes. In industry, interdisciplinary work is the rule rather than the exception, and potential employees who know how to work with teammates outside their own specialized areas of expertise are highly valued.

The continuing increase in and emphasis on interdisciplinary research has important implications for faculty, graduate students, and institutions of higher education. These issues will be further explored in other areas of this report. Colleges and universities are traditionally organized according to disciplinary structures, and many have now strategically overlaid disciplinary structures with supportive units or new procedures in order to facilitate interdisciplinary interactions and research. The integration of these overlaid structures with the more traditional structures already in place needs to be articulated to optimize interdisciplinary research and outcomes.

The challenge for disciplines is not to become interdisciplinary per se, but to be responsive to new discoveries and challenges associated with both scientific innovation and pedagogy.

Research Working Group, IGERT Principal Investigators

Funding agencies have a parallel challenge: they must maintain support for advances by core disciplinary research while also supporting research that cuts across disciplines. While federal funding agencies express the need for interdisciplinary approaches to problems, their structures and practices fall short. Funding agencies have responded by funding multi-investigator, interdisciplinary proposals or problem-based proposals (such as Department of Energy Centers organized around "grand challenges"). However, even in those cases where there is a call for more interdisciplinary research proposals, the proposals received are often reviewed by panels or study sections that may not be structured to handle the various disciplines reflected in the proposal contents. There continue to be concerns about the locus of review and funding when a proposal with an interdisci-

Assessment of the impact of both the technology and educational outcomes (of interdisciplinary research) is extremely difficult. A first difficulty is the time lag between when a change is implemented and when outcomes can be measured.

Research Working Group, IGERT Principal Investigators

plinary theme is handled through a traditional review mechanism.

Measuring Interdisciplinarity in Research

Although there has been a great deal of discussion concerning the impacts of and need for interdisciplinary research, it has been challenging to explicitly measure its value. Measures of the value of interdisciplinary research and its impact can be framed as short-term (research breakthroughs, development of new academic programs); intermediate-term (effects on industry, public policy, the workforce); and long-term (creation of new disciplines). Societal impact can be framed in the same way: broadening participation in the short-term; developing a more flexible and diverse workforce in the intermediate-term; and attracting more K-12 students to science and engineering in the long-term.

The degree to which a specific research program is interdisciplinary and the extent of the impact of such a program may be measured by the following factors, some of which are easily recognized, and some of which will require a fundamental definition of how to develop a measurement:

- Multi-PI/co-PI external funding;
- Numbers of people (faculty, graduate students, undergraduates) actively involved in producing collaborative outcomes such as multi-authored papers in high-impact journals;
- Filing of patents that are interdisciplinary;
- Level of transformation produced (interdisciplinary research should partly justify its existence by producing levels of transformation not possible within disciplines); and
- Connectivity among participants (are they well connected and how wide is the connectivity).

The need for continued support of single investigator, focused research proposals is clear. However, it is equally clear that there need to be efforts on the part of federal funding agencies to foster and support interdisciplinary research.

Research Working Group, IGERT Principal Investigators

Recommendations for Advancing Interdisciplinary Research

Universities

- Organize discussions about research around achieving open-ended scientific discovery and addressing social challenges rather than framing them in terms of disciplinary versus interdisciplinary science.
- Consult with and learn from industry on how best to achieve teamwork on interdisciplinary research problems and how to prepare people for it in the future.
- Develop short-term, intermediate-term, and long-term measures of success of interdisciplinary research, encompassing internal effects on pedagogy, the structure of academia, and development of a diverse workforce in science and engineering, as well as external effects on industry, society (societal problems), and policymakers.
- Form research teams driven by problem-oriented research challenges that serve to defocus emphasis on whether a given research challenge is disciplinary or interdisciplinary.
- Remove disincentives and create incentives for faculty to engage in interdisciplinary research.

Recommendations for Advancing Interdisciplinary Research – Continued

- Develop new models of university organizational structures and funding to facilitate interdisciplinary research.

Funding Agencies

- Reduce the boundaries between disciplines at each of the funding agencies to facilitate cooperation on review and funding.
- Maintain a balance of funding between disciplinary and interdisciplinary research, emphasizing scientific problems as the major determinant in the types of funding programs in the portfolio.
- Increase the numbers of grants supporting interdisciplinary research and training clusters and centers in order to enhance the total investment for interdisciplinary research.
- Because the impact of discoveries is often unforeseen, maintain a portfolio approach to research funding including both research with expected shorter term practical and economic impact, and research with less defined but potentially longer term impact.
- Foster interdisciplinary research at the individual research grant level in addition to the larger interdisciplinary grants. Include more reviewers who are receptive to and conversant with interdisciplinary research. Multiple disciplinary reviews are not the same as reviews by colleagues who are experienced in interdisciplinary collaborations.
- Effectively collaborate with other funding agencies and other constituency groups, such as industry or states, and learn from each other's experience regarding interdisciplinary research and education.
- Be aggressive in staying knowledgeable about current and emerging research areas. One mechanism to achieve this goal would be to expand support for workshops in which scientists and constituencies convene to brainstorm responses to critical interdisciplinary research issues.
- Include interdisciplinary skills training as a part of grant-writing workshops.

The Impact of Interdisciplinarity on Faculty

The faculty is a critical driver of interdisciplinary research and education. In response to the demands of the changing research enterprise and the greater need to work across disciplines, the methods for and types of new faculty hires are changing rapidly. Some universities are engaging in interdisciplinary strategic planning for the future, including planning for faculty hires. Types of appointments include cluster hires, joint or multiple appointments, and appointments to other units such as centers or institutes in addition to departments. Universities are clearly adopting a wide range of hiring strategies.

Examples of such hiring processes and faculty appointments include the following:

- At the University of Alabama, cluster hires are initiated by several interdisciplinary centers, but successful candidates decide which unit they want to join.
- At Oregon State University, the interdisciplinary program can make hires, although each hire is typically associated with one department.
- At the University of Washington, a distinguished professor was hired and allowed to bring her/his team.

> *From a faculty perspective, the change in hiring practices has injected energy into campuses, although problems remain.*
>
> **Faculty Working Group, IGERT Principal Investigators**

- At Rutgers University, cluster hires are at the associate professor or higher level only.
- At Michigan Technological University, an interdisciplinary cluster hiring team composed of

researchers in sustainability from across the university invited candidates to select the departments (up to two or three) in which they would be placed.

- At some schools, faculty hires are aligned with strategic strengths. At SUNY Buffalo, for example, faculty hires are aligned to strategic strengths identified via a lengthy bottom-up process.

The principal driver of effective interdisciplinary research in areas amenable to it is the faculty.

Institutions Working Group, Administrators

Faculty members have many intrinsic incentives to engage in interdisciplinary research and education. These include the opportunity to do something new, particularly if faculty are at mid-career; the excitement of addressing large problems with societal significance; a broader range of funding possibilities; opportunities to network with other faculty outside the home department; the fun of collaboration; the opportunity to recruit better and more diverse students; and the knowledge that these students will get what the faculty consider a better education. While these incentives and rewards are important, they must be bolstered by institutional rewards and recognition.

- For new faculty, there may be a risk in engaging in interdisciplinary activities to the exclusion of disciplinary activities and thus the risk of alienation from a disciplinary unit. Because undergraduate teaching still revolves around disciplines, there may be a tension between the faculty role as teacher and interdisciplinary researcher.
- Other challenges for faculty include the need for a broader knowledge base than their single-discipline colleagues, the difficulty for departments to appreciate or evaluate interdisciplinary research, and interdisciplinary team-teaching as an overload.

Is collaboration recognized at tenure time?

Faculty Working Group, Administrators

- At Northeastern University, there has been a change from filling teaching needs to fulfilling interdisciplinary needs with joint departmental hires. It is also common to have hires with joint departmental/center appointments.
- Again at Rutgers University, a faculty member started in chemical engineering but was jointly appointed to chemical engineering and bioengineering after acquiring tenure.

Although there are many attractions for interdisciplinary work, there are also concerns at several levels.

- Faculty engaging in interdisciplinary activities may find that ties to their traditional disciplines, whether through personal relationships or professional society affiliations, may be weakened as a result of being more engaged with other disciplines.

Measuring and Enabling Interdisciplinarity in Faculty Interaction

Innovative measures for the value or success of faculty adopting or participating in interdisciplinary research include fulfilling the needs to:

- Quantify co-authorship from different disciplines with roles and contributions of faculty on interdisciplinary scholarly work explicitly identified. Consider giving each author full credit regardless of authorship position.
- Quantify participation in extramurally funded interdisciplinary research and education.
- Prove the achievement of broader impacts with evidence of policy impact, K-12 curriculum changes, adoption of results by the private

sector, and level of satisfaction within and across programs.

- Quantify the effort involved in developing interdisciplinary initiatives; for example, participation in working groups, development of letters of intent or preliminary proposals, and submission of full proposals.
- Include the number of students supervised who are from other departments as a consideration in faculty evaluation.

Recommendations for Advancing Interdisciplinarity and Engaging Faculty

University Policies and Procedures

In order to foster interdisciplinary work, universities should take the following steps to benefit the faculty:

- Develop mechanisms for faculty with traditional disciplinary expertise to learn and embrace new interdisciplinary approaches and collaborations.
- Develop paths to reduce the potential tension between disciplinary and interdisciplinary interests when hiring faculty.
- Develop new models for evaluation of faculty contributions to interdisciplinary work. All parties should agree on such policies as distribution of grant overhead funds and credit for multi-authored publications, patents, and grants. Faculty should have a mechanism to more explicitly identify and communicate their individual contributions within multi-investigator interdisciplinary projects and publications.
- Remove disincentives to interdisciplinary teaching and research such as teaching overloads, barriers regarding new curricula, and excessive administrative demands.
- Address the incompatibility between traditional hierarchical administrative structures and new interdisciplinary cross-cutting programs.
- Consider separating the research/graduate teaching functions from the academic unit-driven undergraduate teaching mission such that a broader more interdisciplinary view can be developed by faculty collaborators.
- Establish incentives for the faculty to do interdisciplinary research.
- Assist faculty so that they may most efficiently and effectively carry out interdisciplinary research. Such assistance could include a proactive approach to the formation of interdisciplinary teams, including release time in recognition of the time required; mentoring and training of both junior and senior faculty in the skills needed to succeed in interdisciplinary research, including effective communication and team building; identifying external funding opportunities; and providing incentives such as seed funding or release time for interdisciplinary proposal preparation.
- Reward successful interdisciplinary initiatives, for example, allocate space and additional faculty full-time equivalents (FTEs).
- Collect data and evaluate successful models of institutions that have demonstrated success with interdisciplinary initiatives.

Faculty Hiring, Appointments and Assignments

Both for prospective faculty and for current faculty engaging in interdisciplinary endeavors, absolute clarity and transparency are essential in the following areas:

- Policies for tenure, promotion, and raises must be laid out well in advance. These decisions are typically made within departments, and interdisciplinary activities take place across departments.
- Faculty workload assignments should be transparent. If the workload is shared across departments and/or other units, then a formal, written agreement such as a Memorandum of Understanding should be reached among all participating parties. The potential difficulties

of appointments crossing units with different missions and workloads must be recognized and addressed.

- Valuation of work must be explicit, including both traditional measures such as productivity and funding obtained, and nontraditional measures such as formation of interdisciplinary groups; publishing outside the home discipline in collaboration with other faculty; mentoring students outside the home department; valuing course offerings that attract students from other disciplines; and supporting students outside the home discipline. Appropriate rewards must also be made explicit.

The Impact of Interdisciplinarity on Graduate Education

Today and in the future, the most exciting research topics include many that must be approached from the perspectives of more than one discipline. To become successful leaders and innovators in the interdisciplinary science and engineering of tomorrow, graduate students need both disciplinary depth and interdisciplinary education. In part, the debate about the kind of preparation graduate students need is embedded in the enduring discussion on breadth versus depth in graduate education as well as the emerging discussion on the value of transformative research. Moreover, the question of appropriate graduate-level preparation is related to the topics of transformative graduate training and interdisciplinary graduate training. Yet regardless of the type of graduate educational program, it is accepted that disciplinary depth enables scientists and engineers to bring known and respected expertise to the table in any collaborative project. Thus, deep disciplinary knowledge will continue to be critical and must continue to be instilled.

While critical thinking skills, creativity, and the capacity to create new knowledge will continue to be the foundations of all graduate education, so-called "soft skills" must also be developed in graduate students.

Government and industry have had more emphasis on and experience in working in teams than academia and, thus, have expertise in this area that should be utilized and adapted for academic contexts. 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.

In considering what constitutes transformative interdisciplinary graduate training, the following are important elements:

> *Interdisciplinary training will prepare students for the careers of the future, which may be vastly different from the careers of today.*
>
> **Graduate Education Working Group, IGERT Principal Investigators**

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 a part of coursework or during work on a research project.

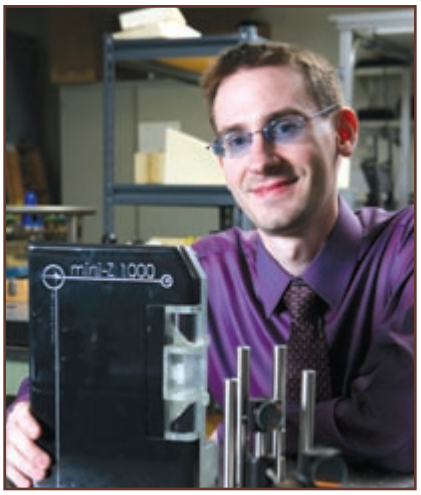
- Training that leads students to work comfortably, independently, and effectively at interfaces, i.e., not only having the knowledge of how interdisciplinary teams could be put together and how to work with people in other fields, but also how to develop research

vision and carry out the research at interdisciplinary interfaces.

- Mechanisms to help graduate students develop skills that enable them to reinvent themselves throughout their careers, tracking changes in science as knowledge evolves.
- Integration of ethical considerations into professional development of graduate students.

Biologists.[6] Interdisciplinary themes may provide more creative and attractive venues for undergraduate students, improving the retention of creative and diverse students.

Graduate students seeking interdisciplinary training are perceived to have broader backgrounds, more independence, greater creativity, and more willingness to take risks than those entering single-discipline



> *Strong core disciplines still provide an important foundation for undergraduate study, but undergraduate exposure to interdisciplinary themes can be a strong value-added component.*
>
> **Academic Institutions Working Group, IGERT Principal Investigators**

In addition to its importance as an element of transformative graduate training, interdisciplinary research strongly attracts students. K-12, undergraduate, and graduate students alike are excited by the chance to work on problems they see as relevant and important to society, which are often interdisciplinary problems. There is an ongoing discussion whether interdisciplinary graduate education, particularly in areas such as sustainability, may be particularly attractive to women and minorities.

Students at the undergraduate level need to develop flexibility earlier on if they are to move into interdisciplinary fields at the graduate level. Some undergraduate institutions are becoming more interdisciplinary in their undergraduate curriculum as occurred in response to the National Research Council's Report *BIO 2010: Transforming Undergraduate Education for Future Research*

programs. Graduate students getting interdisciplinary training are perceived by faculty to become highly motivated, focused, willing to tackle complex problems, more creative, and more willing to take risks. They may also acquire the flexibility necessary to transform themselves throughout their careers as research opportunities change.

Graduate students undertaking interdisciplinary research are strongly impacted by a number of factors. These factors include the number of faculty from different areas with whom they interact, as well as the complexity and breadth of current research topics, which

demand of them a different knowledge base than that required for disciplinary research. Positive impacts of conducting interdisciplinary research are developing skills to approach problems that cannot be solved by single disciplines and a broader range of faculty input and guidance. Potential negative impacts may include less specialized training in certain areas, a less-well-marked professional identity, and a more nebulous set of criteria for success. Finally, the departmental structure of resource allocation can sometimes negatively impact students who work between departments.

Interdisciplinary research can be an effective means of broadening participation by creating bridges between minority-serving institutions (MSIs) and majority-serving institutions at several levels. Examples of the way that these bridges may be built are as follows:

> *We must do more to promote and support undergraduate interdisciplinary training.*
>
> **Graduate Education Working Group, Administrators**

- Interdisciplinary research projects can enhance the research infrastructure available to faculty and students at MSIs. Collaborative research projects enable cost-effective leveraging of NSF's and other agencies' investments in research infrastructure.
- Research ties often lead to educational ties, particularly at the graduate level. For example, teleconferenced research group meetings are the first step in a natural progression that can lead to the sharing of research seminars and graduate courses.
- Interdisciplinary research is an effective means for building strong recruiting pipelines between MSI and non-MSI institutions. For example, students from MSIs who work on cross-campus interdisciplinary research projects are more likely to consider graduate or postdoctoral positions at the partner institution.

- Strong faculty-to-faculty connections are invaluable in recruiting. Faculty at MSIs can be outstanding ambassadors for large research institutions. In some cases, these pipelines can be formalized through bridge programs. The NSF's Partnership for Research and Education in Materials (PREM) program is an excellent example of the bridging role between MSIs and majority institutions that interdisciplinary research may serve.

New approaches to interdisciplinary training include admissions policies that allow students to make choices concerning traditional departments or interdisciplinary programs or mixtures of these; common introductory graduate courses shared among departments; co-advisors from different disciplines; rotations across research laboratories; designated emphases, specializations, or concentrations; interdepartmental programs that cut across departments; new structured interdisciplinary programs; and individually designed interdisciplinary programs.

Examples of mechanisms to allow or promote student flexibility and breadth include the following:

- At SUNY Buffalo, emphasis on interdisciplinary education has led graduate directors from different engineering and physical science departments to begin developing common introductory courses shared among departments. These courses create space in the curriculum to do more interdisciplinary work at the upper levels.
- At the University of California-Davis, one of the mechanisms used to allow greater flexibility and breadth while ensuring depth in a recognized discipline/field is the "Designated Emphasis (DE)." The campus has a number of DEs, such as the DE in Biotechnology and DE in Biophotonics, which allow Ph.D. students from a variety of graduate groups/programs to receive additional training in a particular interdisciplinary area that is recognized on their diplomas and transcripts. For example, they may complete a Ph.D. in Chemical Engineering along with a DE in Biotechnology. This approach provides a formalized structure that is similar to "specializations" or "concentrations" at other institutions. One of the most important considerations is to strike a balance between disciplinary expertise and interdisciplinary training.
- The Pennsylvania State University offers graduate students a dual-title graduate degree program. Students enter through a discipline-based graduate program and must then apply to and be

> *Providing opportunities to participate in an interdisciplinary program of study may enhance efforts to recruit a diverse student body. The integration of undergraduate and graduate training should be enhanced in order to improve the recruitment of a diverse graduate population. The pipeline needs to be broadened at the undergraduate level...*
>
> **Faculty Working Group, IGERT Principal Investigators**

admitted into the secondary area of study for substantial coursework under the supervision of a faculty advisor from that area. The Graduate Council must approve any newly constituted dual-title degree. The student's diploma carries the name of both the major and the dual-title offering.

- Another mechanism to encourage interdisciplinary, collaborative research is to allow students to include jointly authored chapters in their dissertations. Graduate schools at the University of Idaho and the University of Minnesota allow students to include chapters that are co-authored by multiple students, i.e., the same chapter is used in multiple dissertations. This practice goes a step beyond allowing jointly authored chapters to be included in the senior author's dissertation, which most universities do.
- Another novel approach is the ACCESS program at the University of California-Los Angeles in which students are admitted to graduate study in a given interdisciplinary field and receive funding pledged by participating departments before they have even selected the particular degree program in which they will enroll. They can then select the department and research group they will join later on in their program. This approach may be easier to implement in some fields than others. For example, such a rotation system is common in biology but not in engineering, in which students usually join research groups within their first year.
- The "Matrix" organization employed at Michigan State, the University of Minnesota, and the University of Idaho consists of interdepartmental programs that enable collaboration, interaction, and joint efforts among students and faculty in different departments.
- At the University of Florida, students may enter an interdisciplinary program and then decide on the department with which they have an affinity, giving them exposure and options across disciplines.

The ability to effectively work in teams to solve complex problems will be essential to many careers in the future.

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- In addition to Interdepartmental Degree Programs, the University of Michigan offers graduate students the option of combining studies from two Ph.D. programs that will lead to a single Ph.D. (the Student-Initiated Degree Program).
- At the University of Maine, students in the Interdisciplinary Ph.D. (IPhD) program must establish an interdisciplinary graduate committee and negotiate both the program of study and their support with relevant faculty members.

Researchers with interdisciplinary training and a solid disciplinary foundation will be required for many careers of the future.

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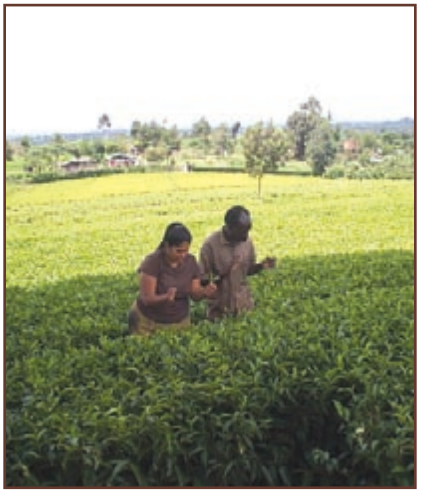

- Arizona State University has developed multiple platforms by which students may enter doctoral programs: they may enter into a more traditional Ph.D. program heavily grounded in a discipline; they may enter through a traditional Ph.D. program that has developed a host of concentrations that are shared by other interdisciplinary programs and be in courses with students from other disciplines (within the concentration); or they may enter truly interdisciplinary Ph.D. programs where students are part of a more interdisciplinary

world and yet can take concentrations and coursework in other programs. In the university's experience, the key is to find the best match for the students depending on their goals, perspectives, and career aspirations.

> *Future STEM graduates must be able to explain why science matters to society and how basic science and technology relate to each other.*
>
> **Graduate Education Working Group, IGERT Principal Investigators**

Emerging fields are expected to present new job opportunities. The promise of a career after graduation is a strong motivator for graduate students to acquire the skills and expertise they will need for these careers and to complete their degrees. Flexibility and adaptability will be hallmarks of successful scientists of the future, and while interdisciplinary training may not be an advantage in obtaining positions defined by single discipline expertise, it will improve a graduate's possibilities of obtaining other positions.

In addition, there is an important role for training programs that make it possible for graduates to adapt to changes in career opportunities that they face after graduation and to plan for flexible career paths. It may be important to screen applicants to graduate programs not only for academic prowess in the discipline, but also for evidence of leadership, communication skills, and teamwork experience that would enable them to be flexible in their careers.

Measuring and Evaluating Interdisciplinarity and Its Impact on Graduate Education and Students

Evaluation of interdisciplinary educational programs might include topics as outlined below, some of which are easily measurable and some of which will require new methods of measurement.

- Numbers of students attending meetings outside their home disciplines;
- Number and quality of team-taught classes bridging multiple disciplines and academic units;
- Student participation in interdisciplinary collaborations and leadership roles in interdisciplinary teams;
- Publication records of the students in the program, including joint publications across disciplines;
- Compositions of thesis committees that include an interdisciplinary mix;
- The nature of the research done as described in the thesis abstracts;
- Comparing interdisciplinary theses and dissertations with those of students in traditional departments for impact through, for example, citations, publications and/or citations in influential journals; and
- Opportunities and career outcomes for students after graduation. Specifically:
  - Does the employment obtained meet the student's goals?
  - Do students get jobs advertised as interdisciplinary?
  - Do students with interdisciplinary training have different career trajectories than students who have not? Do they advance more rapidly, have greater flexibility, or follow different career paths?
  - Do these students contribute to discoveries at the "white spaces" between disciplines?
  - Do they more often become entrepreneurs?
  - Are students with interdisciplinary training effective educators, communicators, and team builders?

> *As a nation, we cannot continue to rely on the availability of international talent.*
>
> **Graduate Education Working Group, Administrators**

Recommendations for Future Interdisciplinary Graduate Education

- Undergraduates should be better prepared to do research and should have sufficient breadth to undertake interdisciplinary research when they become graduate students.
- Graduate students should be better prepared to formulate and implement broad-based interdisciplinary research questions and helped to develop better basic analytic and quantitative skills.
- New learning technologies should be integrated into graduate education.
- Graduate education of the future should free itself from the "3-credit intellectual structure" and begin creating more immersion and module experiences that focus on knowledge and competencies with appropriate learning outcomes at the end of the experience. As the breadth and depth of knowledge and skills required by interdisciplinary students increase, the organization of training experiences must be reconfigured for the most effective and efficient delivery.
- Mechanisms should be developed to support teamwork in graduate education and in thesis topic research.
- Models for transformative interdisciplinary graduate training may be found in successful collaborations from the past where interdisciplinary teams made incredible advances. This approach could be used more broadly to engage young scholars from disparate disciplines to tackle significant scientific challenges and societal problems. It would foster collaborative efforts in fields where single-investigator research is traditionally more common.
- Specific outcomes for skill development in the broad topic of professional skills need to be developed and training needs to be matched to these outcomes. Skills for communication and engagement with the public; training in ethics and responsible conduct of research; global awareness; and the ability to use new learning technologies, incorporating more cooperative and collaborative learning techniques and greater breadth should be included.
- Recognizing the unique stresses on graduate students in interdisciplinary programs, mentoring and tracking should be carefully planned.
- Funding mechanisms within the university are typically tied to departments but should be more portable. A funding mechanism for the first year of graduate school should allow greater exploration prior to choosing an advisor and research area. Further, support mechanisms should be found to fund graduate students in a way that allows and encourages their education and research to cross institutional units.
- Multi-year support should be guaranteed, but a mix of experiences should be ensured, including teaching experience for those aiming at careers in academia.
- Dissertation-year fellowship support is desirable so that graduate students may carry out interdisciplinary thesis research.
- Building collaborative interdisciplinary research involving both minority-serving and majority institutions should be utilized as a means to broaden participation in science and engineering.
- Credentialing through dual-degree programs, certificates, minors, concentrations, designated emphases, or other means should be found to identify a graduate student's interdisciplinary training and potentially aid in communicating both disciplinary depth and interdisciplinary breadth to potential employers.
- While there is a need to increase the number of U.S. citizens and permanent residents in science and engineering so that innovation is not outsourced, admissions policies should take into account not only student demand and student funding availability but also workforce needs and the placements of graduates in specific fields, including interdisciplinary fields.
- Recruitment of underrepresented minorities to STEM graduate study should focus on growing the entire pipeline rather than redistributing a fixed number of minority students who would be bound for graduate school in any case. Interdisciplinary research on topics of societal significance can be an important attractant.

The Impact of Interdisciplinarity on Academic Institutions

The magnitude and scope of interdisciplinary research—and structures and incentives to support it—vary significantly across academic institutions. Those institutions that have focused on disciplines that are historically based on solitary rather than collaborative scholarship are by design less interdisciplinary in structure and outlook. Both the size of an institution and the amount of disciplinary teaching responsibilities have an important impact on the faculty's ability to focus on and the freedom to pursue opportunities outside their own disciplines. Small departments may not have the resources to allocate to interdisciplinary research or teaching without threatening their ability to deliver their core curriculum. Yet smaller institutions may also have the advantage of being able to implement change in targeted, strategic areas more quickly. Larger institutions may have more resources and may have more opportunities to "grow" interdisciplinary research or education at relatively little risk.

Disciplines are not fixed in time but continue to evolve, and thus the university must adapt administratively and structurally to accommodate this evolution. Departments may retain the same title, but they can be quite different than they were several decades ago. Examples include Biology and Mechanical Engineering. Some research areas, such as Materials Science, did not exist as disciplines until quite recently. Some departments, such as Neuroscience, began as interdisciplinary endeavors, and sometimes formation of new departments takes place long after their founding disciplines are recognized, as in the case of Computer Science. In still other cases, research centers and institutes rather than departments have been created to bring faculty together to work on research problems that cross disciplinary boundaries.

Evolution is pervasive!

Academic Institutions Working Group, Principal Investigators

Changes in departmental and university practice are often based on new research challenges, and these changes are numerous. Traditional departments are hiring faculty outside their own disciplines (chemists hiring biologists, chemical engineering units hiring chemistry and biology majors). New interdisciplinary departments are naturally

evolving from cluster hires or centers. Traditional departments are beginning to look outward, and their faculty are more connected across disciplines. Faculty may have joint or multiple appointments. Physical locations of faculty from traditional departments and interdisciplinary programs may be at various places on campus. Faculty offices may be in a centralized location but their laboratories may be in other buildings where equipment can be shared across disciplines. These new structures are often formed based on new challenges, and not on the core discipline, providing a context in which to engage and connect faculty.

Central units can facilitate interdisciplinary research by the type of faculty positions created and by providing proximal research space and core facilities. Continued successful faculty collaboration requires recognition of the importance of these interdisciplinary efforts as they are frequently outside the usual criteria for tenure and promotion.

Strategic faculty hiring with shared positions between departments can be key to fostering the development of new areas of interdisciplinary collaboration. Success in these shared

positions requires clear and transparent understandings between deans, department chairs, and faculty about promotion and tenure criteria.

While the incentives for interdisciplinary collaboration are substantial, there are also significant disincentives for change toward interdisciplinary research and education. Among the most important disincentives are structures and policies that place disciplinary research and training in conflict with interdisciplinary research and training or that do not support the infrastructure required for interdisciplinary success. Observations from the workshop regarding structure and policy challenges include the following:

Many pressing problems requiring solution are interdisciplinary, so there is a mismatch between current disciplinary structure and the nature of inquiry.

Graduate Education Working Group, IGERT Principal Investigators

- Policies pertaining to faculty incentives and rewards including tenure and promotion criteria are often implemented primarily by departments.
- Stringent within-discipline accrediting criteria at the institution can limit shared faculty time for interdisciplinary teaching and research.
- Departmental responsibilities for the undergraduate curriculum can impact not only faculty participation in interdisciplinary activities, but also graduate student participation through heavy requirements for departmental teaching assistantships that are important for student support.
- The current ranking systems by a variety of enterprises, including the National Research Council, have taxonomies rooted in traditional disciplines. These rankings are used both externally and internally to evaluate programs and departments. Those programs that have moved toward interdisciplinary education are ranked inappropriately or not ranked at all and, therefore, are at a disadvantage for applicants using the ranking systems as important criteria in evaluating their choice of which institutions to attend, or administrators valuing the programs within the institution.
- Research and administrative staff members are impacted by interdisciplinary programs, since they must respond to a broader clientele. The financial support for these individuals can be a shared responsibility among various central units or they can be temporary positions paid from any interdisciplinary funding (e.g., IGERT). The former model provides the most stability but is the least used. The second, soft-money solution is the more common and is the least desirable for many reasons including lack of stability, insufficient funds for these functions, and temporary staff that lack institutional memory

or sufficient training in grants or academic management processes.

- There can be a major impact on grants management by the institution, since interdisciplinary proposal submission and management are more complex. This impact can be a burden for small departments or potentially confusing if there is not sufficient clarity on the process.

In addition, several challenges arise in measuring productivity and assigning credit for interdisciplinary endeavors across institutional units:

- Perspectives concerning authorships differ among disciplines (e.g., perceived merit of single versus multi-author publications, author order in recognition of contribution, etc.),
- The assignment of credit for collaborative products (proposal submission, funding, graduate thesis work) is difficult.
- FTE distribution across units for courses with students enrolled from different disciplines often differs.

The importance of interdisciplinary collaborations for the future of the scientific enterprise has also prompted examination internationally, and models for interdisciplinary research and graduate education are being developed that succeed in respecting existing cultural differences. It is important to explore institutional arrangements that might be usefully adopted or adapted. The U.S. model of graduate education focuses on purely academic institutions and independent research institutes, most of which are structured much like academic institutions.

In contrast, many European models linking interdisciplinary research with graduate education include much closer collaborations between academic institutions and the private sector. The private sector collaboration can work very well for both basic and applied research, depending on the field and industry involved. A major limitation, however, is the conflict of interest between the faculty member's freedom to publish and the private sector's intellectual property position.

Another common research and education model that is used outside the U.S. is interdisciplinary research and graduate education concentrated in government laboratories. The current limitations in the U.S. for the government laboratory model compared to other countries include different models of primary and secondary education in other countries, different models for the structure of the scientific workforce, different accrediting structures and differing views of and roles of government labs.

The university, department or school must establish metrics to reward interdisciplinary activity.

Academic Institutions Working Group, Administrators

U.S. accrediting associations have been reluctant to grant accreditation to non-academic institutions, so the latter must partner with an academic institution to be accredited for graduate education. The principal tension is the perception that the faculty of one unit is responsible for the teaching and the other gets the benefit of the trained student.

Some examples of international models include:

- The Max Planck Institutes (Germany) model for industry and government participation along interdisciplinary themes.
- The Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) model in which industry, government, and academia collaborate with aspects of a think tank operation including visiting international scientists, a fluid and open environment, numerous student opportunities, an understanding of industry needs, and consultancy are a normal expectation for CSIRO researchers.

The most important incentives for interdisciplinary research and education are that they attract and retain high-quality faculty and students.

Academic Institutions Working Group, Administrators

The increasing importance of graduate education at international sites serves as a reminder that science and engineering are global, and that U.S. Ph.D. graduates will be in competition with doctoral graduates from abroad. The U.S. must continue to nurture creativity and develop those skills that will serve its graduates well in the future.

Measuring Interdisciplinarity in Academic Institutions

- Generally speaking the same metrics used to evaluate disciplinary research and education (e.g., publications, funding, student outcomes) can be used to evaluate interdisciplinary programs, but they need to be evaluated independently.
- Specific metrics need to be developed at all levels—faculty, student, and institutional.

Recommendations for Supporting Interdisciplinarity in Academic Institutions

- Institutions must be strategic in planning for investment in interdisciplinary research and education based on their strengths, sizes, and types.
- Institutions should move from hierarchical structures to more dynamic and flexible structures in which faculty have some fluidity of movement between or across disciplinary homes.
- Physical space and shared facilities such as microscopy unit, analytical labs, etc., that bring people together should be provided to support collaborative work.
- Interdisciplinary graduate education should, in most cases, remain solidly based in disciplinary programs while allowing for a mechanism for new programs to evolve.
- New faculty positions for interdisciplinary research and education require clarity of expectations, and all parties must be included in the contract.
- New elements of promotion and tenure guidelines need to be added to include recognition and reward for contributions to interdisciplinary research and education.
- Support for interdisciplinary research and education should be extended into undergraduate education.
- Support is required for administrative help and other personnel and may need to include funding sources external to the institution.
- Links between majority and minority institutions should be forged in order to take advantage of the attraction of interdisciplinary research to broaden participation in science and engineering.
- Institutions should explore establishing internal granting programs that require interdisciplinary collaboration.
- Ways of better organizing the institution should be found to take advantage of new external interdisciplinary funding opportunities.