Transformative Research at Predominately Undergraduate Institutions

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Preface

The first decade of the 21st century has been marked by a growing awareness of the fragile state of our economy, environment, public health, and national security—all areas highly dependent on research and technology. Over the same period, we have witnessed a degree of national anxiety regarding the strength of our country's research enterprise, which underpins our ability to innovate and provide leadership in all of those areas. Once regarded as pre-eminent, the United States' research portfolio more recently has been characterized as under-funded, while the processes used to select projects strike many as overly conservative. Meanwhile, other countries have been making significant investments to enhance their research enterprises, and as a result they increasingly challenge our leadership in various disciplinary and interdisciplinary fields of research. In addition, our nation's management of its research portfolio has led many researchers and students to leave research or opt not to pursue careers in research- and innovation-intensive fields that they perceive as too unwelcoming and unrewarding.

It was against this background in 2005 that an influential National Academies report appeared entitled *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, http://www.nap.edu/catalog/11463.html. The report noted that "reducing the risk for individual research projects *increases* the likelihood that breakthrough, 'disruptive' technologies will not be found—the kinds of discoveries that yield huge returns." One of the recommendations labeled as "most urgent" therefore was: "Sustain and strengthen the nation's traditional commitment to long-term basic research that has the potential to be transformational, to maintain the flow of new ideas that fuel the economy, provide security, and enhance the quality of life."

During this period, the National Science Board (NSB), which oversees the National Science Foundation (NSF), also organized a Task Force on Transformative Research that met during 2004-06. The task force's 2007 report, entitled *Enhancing Support of Transformative*

Research at the National Science Foundation, http://www.nsf.gov/nsb/documents/2007/tr_report.pdf, provides the following definition:

> *Transformative research is defined as research driven by ideas that have the potential to radically change our understanding of an important existing scientific or engineering concept or leading to the creation of a new paradigm or field of science or engineering. Such research also is characterized by its challenge to current understanding or its pathway to new frontiers.*

The National Academies' 2005 report, which had been requested by members of Congress, galvanized action in the form of the *America COMPETES Act* of 2007, http://science.house.gov/legislation/leg_highlights_detail.aspx?NewsID=1938. The *America COMPETES Act*, which drew broad bipartisan support, in part "expresses a sense of Congress that each federal research agency should support and promote innovation through funding for high-risk, high-reward research."

Those welcome developments underscored the notion that promoting transformative research is a *national* responsibility that will determine how effectively we compete in the global marketplace. Academic institutions that conduct research are in an ideal position to promote a culture of supporting transformative research and innovation, both through the research projects that are conducted and the students who are trained to become our next-generation technical workforce.

The Council on Undergraduate Research (CUR) is to be commended for convening a meeting of academic leaders from predominantly undergraduate institutions (PUIs) in June 2009 at Snowmass, Utah, to consider how best to support transformative research at such institutions. Support for the meeting from the National Science Foundation, Research Corporation, and the American Chemical Society's Petroleum Research Fund provided a strong endorsement of the conference's objective.

Predominantly undergraduate colleges and universities have a rich history of contributing to our nation's research excellence. Meeting attendees recognized that many of their colleagues and undergraduates were already engaged in transformative research projects on their campuses, ranging from contributing to large-scale efforts like the search for gravitational waves to individual research projects associated with emerging fields like systems biology. The conference was characterized by animated conversations regarding how to enhance this kind of research and ensure that it is valued and recognized as integral to the misson of these institutions.

This volume represents a compilation of the many excellent ideas that were presented during the course of the meeting. As government, academic, scientific and business leaders think about transformative research and how to advance it, PUIs have much to share in terms of experience with, and models for, promoting it. Enhancing transformative research will entail challenges in every aspect of the academic culture, including administrative organization, curriculum, space, faculty reward structures, and intellectual property and technology transfer. The voices of PUIs are integral to this national conversation about transformative research, and the models that PUIs develop will help inform the actions of the broader academic research community. This volume is certain to stimulate a lively dialogue that will raise consciousness and promote purposeful reforms in our research enterprise. There is much work to be done, and our nation more than ever needs the ingenuity of its entire research community.

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Executive Summary

Reviewers of grant proposals submitted to the National Science Foundation (NSF) are required to assess the intellectual merits and broader impacts of the proposed work. NSF recently altered the wording of the review criteria for intellectual merit asking reviewers "to what extent does the proposed activity suggest and explore creative, original, or potentially transformative concepts". The inclusion of an evaluation of whether the proposed research is potentially transformative grew out of the recommendation of a task force assembled by the National Science Board (NSB). The NSB provides oversight for, and establishes policies of the NSF.

The NSB report titled *Enhancing Support of Transformative Research at the National Science Foundation* (http://www.nsf.gov/nsb/documents/2007/tr_report.pdf) provided the following definition of transformative research.

> *Transformative research is defined as research driven by ideas that have the potential to radically change our understanding of an important existing scientific engineering concept or leading to the creation of a new paradigm or field of science or engineering. Such research also is characterized by its challenge to current understanding or its pathway to new frontiers.*

The NSB report also states that transformative research "has the capacity to revolutionize existing fields, create new subfields, cause paradigm shifts, support discovery, and lead to radically new technologies." As such, transformative research is often likely to involve high-risk work with the potential for high-impact outcomes if successful. The NSB report notes that high-risk, high-impact projects do not "fare well wherever a review system is dominated by experts highly invested in current paradigms" and "during times of especially limited budgets that promote aversion to risk."

By specifically asking reviewers to evaluate whether the proposed work is potentially transformative, the expectation is that proposals describing high-risk, high-impact projects will more likely be funded in the future. The NSB report goes on to note that science progresses in two fundamental and "equally valuable" ways. The "vast majority" of scientific understanding occurs in an incremental, or evolutionary, process. Revolutionary work in which dramatic advances in scientific understanding takes place are acknowledged to occur less frequently.

The addition of the words "potentially transformative" to the intellectual merit criteria for NSF proposals without the involvement of faculty members and administrators at predominantly undergraduate institutions (PUIs) in the process caused concern among the PUI community. Furthermore, PUI faculty members and administrators questioned whether this additional criterion would reduce the ability of PUIs to secure research funding from NSF. The NSF Research at Undergraduate Institutions (RUI) Program, which the NSB created in response to requests from CUR and the PUI community in the 1980s, is unique in allowing the principal investigator to provide an additional five-page impact statement. Inclusion of the impact statement in RUI proposals recognizes that the research infrastructure at many PUIs is often less than that at many doctoral-granting institutions and that the pace at which research is completed at PUIs is often slower as well. The significant barriers to research that exist at many PUIs may limit the ability of faculty members at these institutions to conduct transformative research. With a grant from the NSF and additional support from Research Corporation for Scientific Advancement and the Petroleum Research Fund of the American Chemical Society, the Council on Undergraduate Research (CUR) brought together faculty members, administrators and other stakeholders for a summit meeting to examine the role of transformative research at PUIs.

Participants at the meeting explored three broad topics:

(1) Should faculty members at PUIs pursue potentially transformative research?
(2) Why should funding agencies support transformative research?
(3) How do we promote transformative research at PUIs?

Should faculty at PUIs pursue potentially transformative research?

There is universal agreement among summit participants that a goal of faculty members at PUIs is to conduct high-quality, original research. The outcome of research at a PUI should constitute a contribution to the discipline, ideally in the form of peer-reviewed publications in recognized disciplinary journals. The conclusion of summit participants is entirely consonant with the definition of undergraduate research that has been adopted by CUR, which requires that the work be original and that it represent a contribution to the discipline.

> *Undergraduate research is an inquiry or investigation conducted by an undergraduate that makes an original intellectual or creative contribution to the discipline.*

Summit participants recognize that, for most investigators, the pace of work at a PUI will be slower than what could be accomplished at a doctoral-granting institution. Also, participants appreciate that an important reason for faculty members at PUIs to maintain an active and productive research program is because of the positive educational outcomes for the undergraduate student collaborators. Nevertheless, the barriers to research at PUIs and important educational benefits to the students do not obviate the need for faculty members to conduct high-quality research on important scientific questions. With the aim of conducting high-quality work, and considering the benefits of transformative research to science, society and those who participate directly in the discovery process, summit participants are in agreement that PUIs should encourage their faculty members to pursue transformative research. Of course, encouraging transformative research is different than requiring it. The NSB report makes clear that the majority of research is incremental in nature and transformative discoveries are the exception rather than the rule. Nevertheless, summit participants cited several examples of transformative or potentially transformative discoveries that had occurred in laboratories at PUIs and embraced the belief that PUIs should not shy away from encouraging and pursuing research that is potentially transformative.

Why should funding agencies support transformative research?

Funding agencies support research to advance our knowledge base. Usually, the outcomes of the work are expected to benefit people and society in some way, as scientific challenges are intertwined with societal needs. An increasingly important facet of scientific research is the economic benefits that occur when discoveries are translated into marketable technology. The outcomes of many scientific discoveries have the potential to be economic drivers, none more so than transformative discoveries. The increasing capability of scientific researchers and scientific infrastructure in other countries makes it especially important that the United States continue to conduct the highest quality research that leads to beneficial economic outcomes.

There is also recognition on the part of many funding agencies that the development of skilled human capital is another important outcome of many research grants. An agency like NSF acknowledges this through the broader impacts portion of the review process. Ultimately, though, securing a grant to conduct a research project is predicated on the reviewers' determination that the outcomes of the work, if successful, will represent a significant contribution to the discipline. The assessment of intellectual merits of a research proposal must be satisfactory regardless of the extent of the broader impacts.

Obviously work that has the potential to cause paradigm shifts, create new fields of inquiry and lead to radically new technologies is going to be of considerable interest to funding agencies because of the enormous positive contributions to science and society. By supporting transformative research, funding agencies can challenge institutions to move to the next level, foster the best possible teacher-scholars, encourage creative thinking, encourage risk-taking, foster interdisciplinary collaborations and dialogue, expose the next generation of scientists to the best modern science, and prepare our future scientific workforce. If we are entering an era in which securing funding for research becomes more difficult, the importance of proposing high-quality work with significant outcomes will be heightened.

How do we promote transformative research at PUIs?

PUIs have substantial barriers that can make it difficult to conduct research, let alone transformative research. First among these barriers is a lack of time brought on by relatively high teaching loads and substantial advising expectations. Time is not only needed to complete research, but to generate high-quality ideas for projects. Many PUIs lack the research infrastructure (e.g., support staff, equipment, laboratory facilities) that is found at doctoral-granting institutions. Faculty members at PUIs work with inexperienced undergraduates as collaborators, often over relatively short periods of time. Transformative research, which is often high-risk in nature, is difficult to conduct in such an environment. Yet there are examples of individuals and PUIs that undertake transformative research and high-quality publishable work. These institutions and individuals demonstrate that it is feasible to undertake transformative research at PUIs.

A PUI wanting to promote transformative research must embrace the teacher-scholar as the ideal faculty member. Beyond that, transformative research will more likely occur when individual faculty members, departments and the institution work in a concerted effort to create an environment in which high quality research is expected and supported.

Individual faculty members have the responsibility to initiate and sustain a productive research program. This will include efforts to secure external funding for their research. Given constraints on the availability of funding from those agencies and foundations that have historically supported research at PUIs, faculty members will increasingly need to explore non-traditional sources of funding for their work. This includes industrial sources, the variety of state and regional funding opportunities that exist, and other federal agencies beyond NSF and the National Institutes of Health. Since a key facet of conducting transformative research is generating transformative ideas, it is essential that faculty members network with other investigators by attending conferences and participating in professional development activities such as sabbatical leaves. Maintaining multiple threads within a research program is a way to enhance the likelihood that projects may lead to transformative discoveries.

Departments, and especially department chairs, have an important role in creating an environment that encourages scholarly work. This can involve efforts to incorporate research into the curriculum, both in courses and through opportunities for students to conduct research for credit. Departments decide the details of teaching responsibilities and have the ability to create schedules that provide blocks of time for research. Faculty members at PUIs are often isolated because they are the only person in their field at the institution. Departments have the ability to fill positions in a way that can foster collaborations among faculty members. Departments also have an important role in setting the faculty reward and evaluation structure and can implement policies that promote high-risk, high-impact work that is more likely to be transformative in nature.

Institutions must provide the appropriate infrastructure that will allow research to flourish. Faculty members will need regular sabbatical leaves and opportunities for professional development if they are going to initiate and sustain a productive research program. Adequate facilities, including dedicated research laboratories, equipment, and support staff, are necessary as well. Institution-wide activities aimed at celebrating the scholarly accomplishments of faculty members and students, and institutional programs to support student research in the summer, are other ways to promote research activity. A sponsored research office that can help faculty members identify sources of funding and write more competitive proposals is essential in efforts to promote transformative research. A clear policy on intellectual property and technology transfer is important as well. The institution usually sets the faculty reward structure and decides on the general criteria needed for tenure and promotion. Transformative research will often involve high-risk activities with longer time to publication and may involve dissemination in non-standard venues. A tenure and promotion process that is flexible enough to recognize this reality is important in promoting transformative research.

Many of the research questions that may lead to transformative discoveries involve complex systems that are not amenable to study by a single investigator with a single area of expertise. Individuals, departments and the institution must embrace the cross-disciplinary, team-based, teacher-scholar model to optimize the likelihood that transformative research will occur. Tenure and promotion guidelines must specifically value interdisciplinary work as a way of promoting, rather than hindering, such activities.

Summit participants view NSF's inclusion of an evaluation of the potentially transformative nature of the research in the review process as an opportunity to enhance the quality of research that occurs at PUIs rather than something that will limit the ability to do research at PUIs. Reminding ourselves of the need to conduct high quality scholarly work and striving at the institutional, departmental, and individual level to conduct the best work possible will benefit our students, the faculty, the institution and society.

Why Should Undergraduates and Undergraduate Institutions be Involved in Transformative Research?

Thomas J. Wenzel
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Before examining the place of transformative research at predominantly undergraduate institutions (PUIs), I believe that it is worth examining the general nature of research at such institutions. Often the phrase "research at a PUI" is used synonymously with "undergraduate research," since undergraduates are typically the individuals who collaborate with faculty members in undertaking research and scholarly work on these campuses. Coupling the terms "research at a PUI" with "undergraduate research," however, sometimes leads to what I would argue is an undesirable consequence: the implication that the only meaningful reason to conduct research at a PUI is to provide an enriching educational experience for the undergraduate participants. Such a view runs counter to the founding principles of the Council on Undergraduate Research (CUR).

In the late 1970s, the chemists who founded CUR were concerned about the dearth of funding available to faculty members at PUIs and purposefully set out, primarily through publishing directories of research at PUIs, to demonstrate the high-quality research taking place at these institutions. However, as CUR grew and opened membership to individuals, it was common to hear discussion and debate over the CUR bulletin board in the 1990s regarding a definition of undergraduate research—as if somehow research done by an undergraduate is inherently different from research done by graduate students, postdoctoral associates, or anybody else.

In 1997, in response to these frequent debates, a breakout session at a CUR Dialogue meeting was organized to consider "what constitutes undergraduate research." This group arrived at the following definition, which has since been adopted by CUR and by a group convened at a meeting known as the Undergraduate Research Summit, supported by the Chemistry Division of the National Science Foundation (http://www.bates.edu/x50817.xml):

> *Undergraduate research is an inquiry or investigation conducted by an undergraduate that makes an original intellectual or creative contribution to the discipline.*

There are two important features of this definition. One is that research is original work and is therefore aimed at creating new knowledge. The other is that the work, if successful, is intended as a contribution to the discipline, meaning that it ought to be disseminated among members of the relevant community through established means. In fields other than creative arts, this usually entails publication of the work in a peer-reviewed scholarly journal. Therefore, when a faculty member at a PUI undertakes a research project, it ought to be done with the ultimate goal of publication in the peer-reviewed literature.

No faculty member at a PUI will deny that an important goal of participating in research is to provide a valuable educational experience to the undergraduate collaborators. From a student's perspective, the value of an original project rests on the supposition that it is more difficult to create knowledge than it is to learn something that is already accepted by people in the field. If so, then creating new knowledge has the potential to heighten learning. From an undergraduate's perspective (and a faculty member's as well), working on research that is potentially transformative is likely to be more interesting and relevant, given the potential importance of the contribution to science and society if the project is successful.

In 2007, the National Science Board (NSB) published a report, *Enhancing Support of Transformative Research at the National Science Foundation* (http://www.nsf.gov/nsb/documents/2007/tr_report.pdf). The board's report encouraged the adoption of the following definition of transformative research:

> *Transformative research is defined as research driven by ideas that have the potential to radically change our understanding of an important existing scientific engineering concept or leading to the creation of a new paradigm or field of science or engineering. Such research also is characterized by its challenge to current understanding or its pathway to new frontiers.*

The NSB report also states that transformative research "has the capacity to revolutionize existing fields, create new subfields, cause paradigm shifts, support discovery, and lead to radically new technologies."

When considering whether we ought to encourage faculty members at PUIs to undertake transformative research, I have to wonder how anyone could ever answer "No" to that question. Given the definition and characteristics of transformative research provided by the NSB, who in their right mind would not want to work on transformative research? It seems that everyone—the institution, the faculty, the students, and society—would benefit from participation in transformative research. Presumably everyone conducting research would prefer to undertake transformative research.

The more difficult issue is the extent to which it is possible to conduct transformative research at PUIs. I think everyone will acknowledge the substantial barriers that can make it more difficult to undertake such research at this type of institution. The general lack of infrastructure when compared to research universities and institutes, the high teaching loads, and the inexperience of undergraduate collaborators are three potential barriers that immediately come to mind. However, faculty members at PUIs may have the ability to take on a high-risk, high-gain idea, since our situation is usually not accompanied by substantial productivity expectations (e.g., grants and publications) that require watching out for and preserving one's reputation. Who really cares if I go off on some quest to cure cancer or develop a system capable of splitting water into hydrogen and oxygen? I may have a few colleagues who think I'm nuts, but I certainly do not have a broadly established research reputation that will be tarnished if I pursue a "crazy" idea. And, if I'm successful, think of what it would mean to my students, my institution, and me.

In thinking about key factors that likely to contribute to a person's ability to conduct transformative research, I came up with three. The first is the ability to identify transformative problems or questions and to then generate transformative ideas for solving them. This can be especially challenging at PUIs, where it is often difficult to generate good ideas, let alone transformative ideas, for research projects because of the isolation that many faculty members experience. Faculty members at PUIs are often the sole individual within their subfield. Reduced opportunities to interact with colleagues at other institutions because of limited seminar programs and few chances to travel to professional conferences compound this problem.

The second key factor involves serendipity. I have to believe that some proportion of transformative research occurs through serendipitous discoveries. If serendipity plays a role, then the more projects taking place in a laboratory and the more experience on the part of the investigators, the more likelihood there is that something transformative might be discovered by accident. Most research efforts at PUIs, however, are done on a small scale, with inexperienced investigators.

The third factor is the likelihood that collaboration among faculty peers can enhance the possibility of conducting transformative research. The NSB report states that "by its very nature, transformative research often is challenging to and frequently crosses disciplines." In many ways, colleagues at PUIs are well positioned to develop unique interdisciplinary interactions. With smaller faculties and departments, it is often easier for scientists to interact with colleagues from other disciplines. Also, colleagues from other universities and research institutions are often amenable to collaborations with faculty members from PUIs, in part because of the growing emphasis on showing significant, broader impacts of their work.

If we want to promote transformative research at PUIs then, it seems that we need (1) institutions and departments that expect their faculty members to be "research productive" (that is, to regularly take their work through to peer-reviewed publication), (2) faculty members who strive to be "research productive" and are willing to seek out and learn about new fields of work, (3) focused efforts to help faculty members generate ideas for meaningful research, and (4) an environment that actively promotes collaborations among faculty members as a means toward productivity and the generation of good ideas.

Should faculty members at PUIs be concerned that National Science Foundation (NSF) reviewers are now asked to assess whether the intellectual merits of proposed research have the potential to be transformative? I believe the answer will depend on how the community of reviewers and NSF program officers respond to this expectation over the next decade. The NSB report specifically notes that science progresses in two fundamental and *equally valuable* (my emphasis) ways. It acknowledges that "the vast majority of scientific understanding advances incrementally" in an evolutionary process and that revolutionary work, in which scientific understanding advances dramatically, occurs less frequently.

I will admit that I have never done transformative research as a graduate student or as a faculty member; yet that's not to say that my work has not been important and worth doing. I believe it is essential that we recognize that not all work needs to be transformative to be judged worth doing and worth funding. I think it is essential that we maintain especially high standards and expectations for what we define as transformative research. The NSB report makes clear that transformative research was singled out because high-risk, high-gain work does not necessarily fare well during the review process at NSF. As the report states, transformative research "does not fare well wherever a review system is dominated by experts highly invested in current paradigms" and "during times of especially limited budgets that promote aversion to risk."

If the new wording in the guidelines for NSF reviewers creates a situation in which everybody tries to "spin" the importance of the proposed work and claim that it's transformative, then I believe there is the potential for two unfortunate consequences. One is that we may be right back where we started in the review process, with no good mechanism to actually identify and fund truly transformative research. The other is that I believe it will be more difficult for many investigators at PUIs to put a transformative "spin" on their work, which will be a threat to funding for research at PUIs. The barriers to research at PUIs that I mentioned earlier make it less likely that proposals from such institutions will succeed in the peer-review process and receive funding if everyone is expected to perform transformative research. If we reach a point where the NSF views what the NSB report calls evolutionary research as not worthy of funding, that will pose a threat to the foundation's support of research at PUIs.

It is interesting to examine the following two charts in the report of a 2007 NSF survey (http://nsf.gov/od/ipamm_2007proposersurveyresults/nsf_2007proposersurvey_results_070629.pdf):.

Of the NSF proposals you've **reviewed** during the past three years, what percentage have constituted transformative research (TR)?

Less than 10 %	61.5%
10-25%	23.1%
26-50%	6.1%
51-75%	2.2%
76-100%	1.1%
Not sure what TR is	6.0%

In the past three years, what percentage of the research proposals that you **submitted** to NSF constituted transformative research?

Less than 10%	24.2%
10-25%	14.5%
26-50%	15.6%
51-75%	13.0%
76-100%	22.0%
Not sure what TR is	10.7%

What is striking about this data is that reviewers think only a small percentage of the proposals they review contain transformative research, whereas submitters believe that a much higher percentage of the work they are proposing to undertake constitutes transformative research. Such a mismatch suggests that many submitters may try to "spin" their work as transformative. It will be important to monitor the effect this will have in the review process in the coming years.

My own opinion is that I believe reviewers and program officers are quite adept at seeing through such smokescreens and determining whether or not a particular line of work is addressing a problem or question whose outcome has the potential to be transformative. Therefore, I believe efforts to "spin" work as being transformative will generally not work with reviewers and program officers, and, in fact, could have just the opposite effect. As a result, I do not currently see the inclusion of the words "potentially transformative" in the "intellectual merit" portion of the reviewer guidelines as a threat to funding for research at PUIs.

Similarly, I see no need to include the phrase "potentially transformative" in the assessment of the broader impacts of the project. There is no doubt that participation in research is often a transformative learning experience for undergraduates. Yet, a research grant from NSF does not ask us to document and assess just how transformative this experience is for the student participants, and I doubt that we want to go down that path. For undergraduates, I would much prefer the implicit assumption that they benefit by participating in original research and that it is better if they have the chance to work on what is deemed high-quality research, the best of which is potentially transformative.

The material in this chapter was originally prepared for the Council on Undergraduate Research's Transformative Research Summit held in June 2009.

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How Should (Do) We Promote Transformative Research at PUIs?

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In 2007, the National Science Board released its report *Enhancing Support of Transformative Research at the National Science Foundation*. In it, transformative research was defined as "research that has the capacity to revolutionize existing fields, create new subfields, cause paradigm shifts, support discovery, and lead to radically new technologies."

Prior to that, in September 2004, the National Institutes of Health had unveiled their *Roadmap for Medical Research*, whose goals addressed reducing and/or eliminating roadblocks to research and transforming the way biomedical research was conducted by overcoming hurdles or by filling in gaps of knowledge (http://nihroadmap.nih.gov/). The Transformative R01 was designed to "support exceptionally innovative, high risk, original and/or unconventional research projects that have the potential to profoundly impact a broad area of biomedical or behavioral research" (http://nihroadmap.nih.gov/T-R01/).

President Obama, in an April 2009 speech at the National Academies of Science Annual Meetingannounced the creation of the Advanced Research Projects Agency for Energy (ARPA-E), which will seek to do high-risk, high-reward research related to energy (http://www.nationalacademies.org/morenews/20090428.html).

Examining just these three developments makes it clear that the concept of transformative research and also its basic definition are already inculcated in government philosophy and operational directions.

Further, Arden L. Bement, Director of the National Science Foundation (NSF), indicated in 2007 remarks to the Texas Academy of Medicine that most of the initial truly transformative advances—that is, paradigm shifts, new subfields, radically new technologies, and the like are recognized *post hoc*. Therefore NSF does not want to restrict the focus of work in emerging areas of research. Bement indicated that "having a portfolio of high quality projects that approach a frontier from many different directions that inform the next round of work" is important, because it leads to a "coherent body of knowledge that coalesces." Historically, as a result of this approach, new directions, new technologies, and new subfields have evolved.

It seems to me that basic research will continue even if it is evolutionary and not revolutionary. Yet, one must ask whether the approaches used to answer basic science questions, as well as those used to revolutionize scientific fields in the twentieth century, will be the approaches needed in the twenty-first century. In many cases, significant developments have come from collaborations among investigators working in seemingly disparate fields. For example, the harnessing of atomic energy in the late 1930s and 1940s occurred as a result of physicists, materials scientists and engineers working together. More recently the field of bioinformatics has grown out of the human genome project and has brought together molecular biologists, mathematicians, and computer scientists. Nanotechnology, as a discipline, has grown from the carbon buckeyball and embraces chemistry, materials science, and molecular biology, among other fields.

Clearly, there have been many attempts over the past decade and a half to steer the academy toward preparing scientists for the future by "encouraging" us to change the academic culture to foster collaborations and to promote interdisciplinary training. For example, in the "Roadmap," NIH emphasized the need to change the academic culture to foster collaborations. And prior to the roadmap, NSF initiated the Integrative Graduate Education and Research Traineeship (IGERT) program in 1997 to provide future PhD scientists, engineers, and educators with the interdisciplinary backgrounds needed to catalyze a cultural change at institutions—a shift to a focus on collaborative research that transcends traditional disciplinary boundaries (http://www.nsf.gov/crssprgm/igert/intro.jsp). Even earlier, in the early 1990s, the Merck/AAAS Undergraduate Summer Research Program funded interdisciplinary research grants for collaborations between biology and chemistry departments, in an attempt to encourage such cultural changes at PUI's.

The National Academies Press published *BIO2010 Transforming Undergraduate Education For Future Research Biologists* in 2003. This volume called for connections to be developed between biology and other scientific disciplines to enable interdisciplinary thinking and work to become second nature. The authors pointed out that the ways in which scientists communicate, interact, and collaborate were undergoing rapid and dramatic transformations, driven by the accessibility of vast computing power and information exchange over the Internet (http://www.nap.edu/openbook.php?isbn=0309085357). Likewise, since the mid-1990s, the focus of the Howard Hughes Medical Institute's Undergraduate Science Education Grants Program has steadily moved undergraduate curricula toward developing cross-disciplinary connections. And in June 2009, the Association of American Medical Colleges, in conjunction with HHMI, released a report, *Scientific Foundations for Future Physicians*, that stresses alterations in pre-medical curricula to promote more interdisciplinary and integrative science courses to help students develop a series of scientific competencies (http://hhmi.org/grants/sffp.html).

I believe the key to promoting transformative research at PUI's for faculty members and students involves creating an institutional infrastructure that provides opportunities for high-quality, potentially transformative research to take place—and I believe two important components of this institutional infrastructure are collaborations within and across disciplines, and an interdisciplinary focus in our educational programming. (In another chapter in this monograph, Julio Ramierz outlines other important items that need to be included in this infrastructure, for example, faculty time, funds for faculty professional development, space dedicated to research activities, access to needed and expensive instrumentation, a reward structure that acknowledges faculty effort, and a sponsored-programs office to help with grants acquisition and management.)

In reviewing undergraduate biology programs nationwide for the Council on Undergraduate Research (CUR) and other entities, I have been amazed at the absence of collaborations, both within and across disciplines, in many institutions' research and teaching enterprises. This is in stark contrast to what is seen in industrial, national, or many graduate-school laboratories where "in-house" collaborations are the norm.

As Tom Wenzel indicates in his chapter in this monograph, faculty members at PUIs are often the only ones in their particular area of expertise, thus making it difficult for them to stay engaged in cutting-edge work that might transform their specific subfield. However, this isolation also opens up possibilities and opportunities for collaborations across disciplines within our institutions. Unfortunately this has not yet become the norm in many PUI's, in part due to time commitments but more often due to spatial separation and a silo mentality.

If one examines the design of new science laboratories in colleges and universities, private industry, or the government, one finds that the design trends over the past decade have focused on creating buildings with features aimed at fostering the exchange of ideas among researchers with varied interests. These include open labs, a common library, huddle rooms, breakout spaces, small conference spaces, and the like. (See *Solving the Design Equation: Major Laboratory Trends of this Decade.* R & D Magazine (http://www.labdesignnews.com/LaboratoryDesign/LD0602FEAT_1.asp).

While most us will not have the luxury of being involved in building new science facilities incorporating these features from the ground up, there are approaches we can take to create opportunities for interdisciplinary and collaborative work within our existing facilities. These approaches have been used successfully in graduate and professional schools and in industrial labs. For example, grouping investigators from different backgrounds in either areas of on-going research interests (for example, in neuroscience this could include psychologists, cognitive scientists, biochemists, cell neurobiologists, and neuroanatomists) or grouping investigators based on their need for the same types of instrumentation (GC/GC-Mass spec- plant biologists, environmental toxicologists, chemists, biochemists, etc).

By placing people with different backgrounds in close proximity (providing they have the time to interact), daily communications will ultimately lead to new ideas for investigation. Likewise, these interactions will lead to novel teaching approaches that integrate our fields, thus helping to better prepare our students for what they will encounter in graduate and professional schools and the workplace.

Of note in the recent AAMS-HHMI report on the scientific foundations needed for future physicians is its call to reorganize "educational programs through an integrated, non-departmental approach." This has implications for hiring faculty. Many of our new faculty colleagues already are coming to us from interdisciplinary graduate programs, and they are seeking positions that can provide them with the facilities and colleagues to continue their approach to doing science. Likewise, they are interested in developing curricular approaches that emulate the way they learned their science. So although promoting transformative research at PUI's involves creating an infrastructure that provides opportunities for high-quality, potentially transformative research to take place, it is the investigators who will create the ideas and conduct this work. In my mind we won't have the infrastructure without the investigators, and we should be mindful that many current faculty positions in the U.S. will turn over in the next few years.The NSF 2003 Survey of Doctoral recipients indicated that between 42 and 51 percent of those employed in the biological and natural sciences were over 50, while 34 to 44 percent had received their doctorates more than 20 years earlier. (http://www.nsf.gov/statistics/nsf06320/tables.htm#group3). While we need to ensure that our current faculty members will be able to succeed in securing research funding to support their research, we also need to be thinking about longer-term strategies that will enable us to continue to move our institutions forward.

Another way to promote potentially transformative research in our institutions is to integrate our research into our teaching at all levels. This has long been a driving force in how CUR faculty approach teaching. Yet for many faculty members, the concept of fully integrating their research into courses has been met with resistance based on the concept that students need a basic body of knowledge before they can become involved in research. While I do not disagree in principle, I think there is more we can do to move in this direction.

A novel program that we need to be following is HHMI's new Science Education Alliance (SEA) http://www.hhmi.org/news/sea20090527.html. This nationwide project is in genomics, an area requiring the integration of molecular biology, biochemistry, and computational and computer science skills. Typically, these are areas in our current curricula that upperclass students are exposed to after taking two years of prerequisites. In contrast, the SEA program is aimed at beginning science students. The program is only one year old, but initial outcomes indicate students at this level are successful in research endeavors. Time will tell how effective this approachgetting authentic research questions into our integrated science courses at a very early stage in the careers of our students—will be in promoting transformational research at our institutions.

Supporting student participation in undergraduate research is important in any type of research at PUIs. Many campuses say they can only fund students if faculty members receive external grants. Yet two institutions where I have worked, Canisius College in Buffalo, New York, and now Kentucky Wesleyan College in Owensboro, Kentucky, have used institutional student-aid money to create undergraduate research opportunities for students across all disciplines. Students must compete for the funds by submitting a mini-proposal, and a selection committee determines who receives awards, based on the expected outcomes of a completed project by the end of the academic year. These awards cost the institution nothing additional since they are part of the students' financial-aid packages. Students must earn their awards by working for a faculty member on or off-campus and since these awards pay $8 to $10 per hour, they are attractive alternatives to other off-campus employment. The awards benefit both the students and the faculty members. Similarly, providing for low-cost or free housing for student researchers in the summer can push research programs forward at a faster pace.

Although some institutions may find it difficult to promote transformational research through reduced teaching loads or more frequent sabbaticals, it is possible to integrate a rotating course release into a department. If planned well, this can create time for a faculty member to pursue his or her work. If this is tied into an expected outcome, such as a grant proposal or a manuscript to be submitted by the end of the semester, it can lead to increased productivity and/or make faculty members more competitive when they apply for external funding.

In summary, I believe there are two key factors that we must be aware of if we are going to be successful in creating the infrastructure needed to be competitive players in transformational research——promoting collaborations within our institutions and altering our facilities so we can create opportunities for inter- or cross-disciplinary interactions. Having been at an institution where we had access to time, space, rewards, and instrumentation, but where we often maintained the silo culture typically associated with academe for at least the past 50 years, I can say that transformative research did not happen in those circumstances. However, we found new hires were seeking opportunities to collaborate and work cross-disciplinarily. I am now at an institution that does not have time, space, rewards, or much in the way of cutting-edge instrumentation, so I agree that it is important that organizations like CUR continue to push for inclusion of research in the curriculum and urge funding agencies to continue to support a variety of endeavors to build the scientific enterprise throughout the country.

HHMI has clearly taken the lead in providing opportunities for transforming undergraduate science. Likewise, NSF and NIH have maintained a diversified portfolio of targeted programming that has helped institutions support students, acquire instrumentation, and conduct research. All of these agencies have pushed our institutions to change our approach to doing science. Now, w e must do our part and keep pace with the evolution of how science is done.

One person, one lab, one discipline may become a vanishing paradigm in the twenty-first century or may remain a vital component of the scientific enterprise. No one has a crystal ball to gaze that far into the future. Yet the issues I've outlined are those we must think about if we want to be engaged in research in the future. I agree with Tom Wenzel that good ideas, whether transformative or no, will continue to be funded in the foreseeable future. Our task is to create the environment that will allow these ideas to be created, nourished, grow, and come to fruition.

Promoting Supportive Environments for Transformative Research at Predominantly Undergraduate Institutions

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"Scientific revolutions are inaugurated by a growing sense … that an existing paradigm has ceased to function adequately in the exploration of an aspect of nature to which that paradigm itself had previously led the way."

—Thomas S. Kuhn
The Structure of Scientific Revolutions

Thomas Kuhn in *The Structure of Scientific Revolutions* observed that the vast majority of us who do science are essentially involved in "normal science." Precious few of us can claim to share Mount Olympus with the likes of Albert Einstein, Barbara McClintock, or Charles Townes. In Thomas Wenzel's chapter in this monograph, he notes that a large majority of the respondents to a National Science Foundation (NSF) survey believed that fewer than 10 percent of the grants they reviewed could be deemed transformative research.

If we subscribe to Thomas Kuhn's thinking about how science progresses through revolutionary or paradigmatic shifts, I suspect that the percentage is actually far below 10 percent, at least at the birth of a scientific revolution, when scientific anomalies have accumulated to the point that a radical shift in thinking begins to take shape. Nonetheless, the NSF has adopted this standard as part of the criteria that reviewers are instructed to incorporate into their critical assessments of grant applications. So for those of us who conduct scientific research at predominantly undergraduate institutions (PUIs), where does this leave us? Should we be thinking about alternative careers, perhaps in banking, real estate, or the auto industry?

Before those of us who do the "normal," incremental scientific work become deeply distraught, it is important to remember that the review criteria that we've been handed by the NSF continue to provide great latitude concerning what constitutes intellectual merit. One section asks: "To what extent does the proposed activity suggest and explore creative, original, *or* potentially transformative concepts?" The key word here is "or"—it is not "and"—a crucial distinction in the instructions to reviewers. Some reviewers may weigh the transformative potential of the proposed research more heavily than others, but given the tenor of the conversation at the NSF and the National Science Board, it is likely that reviewers will have, by and large, a balanced view of this criterion.

So for the majority of us at PUIs who are deeply engaged in "normal" scientific research, I think we should let out a collective sigh of relief and then get back to the business of doing the highest quality science our intellects and passions have driven us to do all along. Indeed, for all we know, we may very well be on the path to transformative research. But, as Kuhn himself points out, what may be viewed as progress "lies simply in the eye of the beholder," so whether our work is truly transformative will ultimately be left to the Nobel committee and historians to decide.

So how *do* we promote transformative research at primarily undergraduate institutions? I'd like to frame my response to this question in three parts: First, I'll identify several of the obstacles that may limit our ability at PUIs to engage in transformative research. Second, I'll recommend a few approaches that might help PUIs become crucibles for transformative research. Third, I'll briefly touch on the national effort needed to enable transformative research at PUIs.

What Are the Obstacles?

The range of PUIs across the country is staggering. If we look to the figures from *U.S. News & World Report*, we have just over 1,150 institutions that fit into this category. They vary enormously in size, endowment, and the state of the physical plants. What they share is a tremendous pool of talent among faculty and students that is just waiting to be tapped for the production of leading-edge research, much of it innovative, some of it potentially transformative. Unfortunately, as talented as the faculty members and the students might be, there are realities at many institutions, some harsh—some just problematic—that must be addressed.

Let's first consider that most sacred of ingredients, central to any successful scholarly enterprise: time—having the time to contemplate, to design experiments, to read the research literature, to learn new techniques and approaches, to play in the laboratory. At most PUIs with which I'm familiar, time is as rare as hen's teeth. Our institutions have to pay the bills, and we pay the bills at PUIs by teaching students. Of course, we've chosen this lifestyle because we derive great personal satisfaction by teaching our students, who are the next generation of scientists and leaders. If we are to take the goal of engaging in transformative research seriously, however, heavy teaching loads with large numbers of students creates a significant barrier to attaining that goal.

At a number of institutions, particularly good endowments (even after the stock market meltdown) provide them with the wherewithal to allow their faculty members to focus on a relatively small number of courses and students during an academic year. For most institutions, however, the luxuries of a small teaching load and small classes remain a distant aspiration. Predominantly undergraduate institutions burdened with shrinking budgets struggle to create opportunities such as these for their faculties and students. Truthfully, it is difficult to imagine how faculty members who may be teaching three or four courses per semester, with a large number of students in those classes, would be able to carve enough time out of their day to engage in potentially transformative research.

A key element in promoting the intellectual well-being of faculty at PUIs is professional development. Unfortunately, funding professional-development opportunities is viewed at a host of institutions as a luxury that can't compete with other pressing needs that administrators, trustees, or state legislatures are juggling during these harrowing economic times. As PUIs across the country scramble to pay the bills, I fear that few faculty members will be offered opportunities for professional development.

Further, any working scientist is well aware of the importance of infrastructure. Revolutionary ideas in science don't necessarily require great infrastructure to germinate, but if those ideas are to bloom into the solid empirical work that ultimately substantiates those ideas, significant investments in infrastructure must be made at many PUIs. Numerous institutions across the country lack the adequate equipment, space, and support facilities that will enable scientists to run the experiments demonstrating the scientific anomalies in a research field or illuminating the new paths to transformative discoveries. Indeed, at some institutions one may ask whether the facilities and equipment available to the faculty are even adequate to educate our next generation of scientists, let alone to enable transformative research.

Finally, the reward systems, or lack thereof, at PUIs may sometimes produce psychological or logistical barriers that prevent some of the most talented science faculty members from engaging in "potentially transformative research." I would not be surprised to discover that at many institutions the most talented researchers are also among the most exceptional teachers and the most active college or university citizens. Many of the traits that make for talented researchers, such as inspired imagination, passionate pursuit of an idea, workaholic tendencies, and meticulous attention to the facts, also lead these same individuals to excel in the other arenas of academic life. The danger at many PUIs is that these individuals are rewarded for their excellence with the opportunity to do yet more for their institutions, from serving on a greater number of important committees to teaching larger classes or doing more overloads because of student demand.

Clearing the Path

In light of these obstacles, a job in the auto industry might seem like a pretty attractive alternative. The good news, however, is that there are models already out there that clear the path to transformative research exceptionally well. The bad news is that clearing this path is expensive. Nonetheless, if PUIs are truly committed to promoting transformative research, this financial investment is reasonable and there are several approaches PUIs can

Clearing the Path: An Optimal Formulation

- Teaching Responsibilities
  - Four courses annually
  - Low student-faculty ratios
- Sabbatical Policy
  - Every 7th semester
  - Full-year, paid sabbaticals
- Well-funded Professional Development
  - Workshops
  - Conferences
  - Special emphasis on junior faculty
- Strong grants/development office to enhance infrastructure
  - Preparing and submitting grants
  - Monitoring budget
  - Reporting on grants
- Reward System
  - Release time for research and grant-writing
  - Limit committee responsibilities
  - Meritorious research sabbaticals

Figure 1. This model is designed to maximize faculty time and provide resources that potentially enable faculty members to pursue transformative research. All elements of the model may not be attainable by every institution, but PUIs are encouraged to consider adopting components that are financially feasible and to strive for the elements beyond their reach at present.

take. Not all institutions will be in a position to adopt the recommendations made here (for a summary see Figure 1), but institutions can certainly adopt those pieces that are financially within reach, even if a bit of a stretch, in order to promote transformative research on their campuses.

How might time be created for faculty members to immerse themselves in transformative research? One example to consider is the faculty-support model at Williams College. Faculty members teach four courses per year (although they are also responsible for four-week, winter-term courses every other year). The size of the classes they teach is manageable; 73 percent of the classes have fewer than 20 students and only 4 percent have more than 50 students. Williams has a student/faculty ratio of 7:1. Students receive a lot of attention and a great education; faculty members have time to embark on paths of discovery that may lead to transformative research.

Of course, not many institutions would be in the position to offer all their faculty members four-course teaching loads every year, but in the case of faculty members who are doing leading-edge research funded by federal agencies or private foundations, it would not be unreasonable to offer these faculty members reduced teaching loads to support their research efforts. Some may argue that reducing the teaching loads diminishes the importance of teaching at these institutions. I would argue, however, that these reductions may enable a faculty member to better integrate teaching and research and thus enhance the educational experience of undergraduates collaborating with the professor in the research.

Sabbatical policies at several institutions are most certainly worth highlighting. The sabbatical policies at Williams College and Amherst College, for example, are designed to provide their faculty members with the time to immerse themselves in research on an enviably frequent cycle. A semester's sabbatical at 75 percent to 80 percent of salary is offered after six semesters (that is, three years) of teaching. Amherst also offers an alternative sabbatical program in which a faculty member may take a full year at 80 percent of salary after 12 semesters of teaching.

We can never ensure that a faculty member will engage in transformative research, but policies such as these provide faculty with the necessary time to make a substantive effort toward realizing that goal. Institutions with faculty members who are conducting potentially transformative research that receives extramural support should seriously consider implementing a sabbatical policy that recognizes outstanding faculty members by encouraging them to take more frequent sabbaticals and/or fully paid one-year sabbaticals. The Boswell Family Faculty Fellowship recently implemented at Davidson College, for example, is a competitive fellowship that enables one or two faculty members per year to take a fully funded one-year sabbatical.

Ironically, probably one of the least expensive efforts that an institution can make could be the one that pays the most dividends: offering professional development. If scientists are going to be working at the outer edges of their disciplines, discovering the anomalies that will eventually add up to revolutionary science, they will require regular infusions of scholarly tonic. These infusions come from interactions with colleagues at scientific meetings, from visiting colleagues at their laboratories, from fostering collaborations with colleagues in academe and industry, and from attending workshops aimed at improving their skill sets.

Providing professional-development opportunities to junior faculty members is particularly crucial as they launch their careers. Transitioning into a PUI environment after graduate school or a postdoc can be stressful as junior faculty members begin to juggle all the demands in these environments. So as not to lose their competitive edge, junior faculty members should get special attention to help them keep their research programs on track and energized. Indeed, it is not unlikely that mid-career and more seasoned faculty might also find the atmosphere at PUIs committed to nurturing transformative research energizing. Such institutions are likely to reap the benefits not only of an outstanding research faculty, but also of a rejuvenated, focused, and enthusiastic faculty generally, whose members are ready to work even more vigorously on behalf of their institutions. Predominantly undergraduate institutions need to see professional development of both junior and seasoned faculty members as investments in their institutional futures.

Providing faculty members with a top-quality infrastructure is indeed expensive. If administrators at PUIs conclude that their faculties should be engaged in transformative research, institutions must make a financial commitment to provide the equipment and space that will help propel their faculty's research efforts forward. Realistically, many institutions will not be in the financial position to purchase expensive equipment or renovate space, particularly when they're making every effort to avoid laying off staff during these difficult economic times. At the very minimum, however, PUIs should provide grant-writing support so faculty members can write proposals seeking funding for equipment purchases or renovations. Development offices should team up with faculty members to explore opportunities with private donors or private foundations. Investments in grants offices and development offices can yield significant funds that will enable faculty members to pursue their research with vigor and confidence.

The Grants and Contracts Office at Davidson College is an example of how an institution can partner with faculty members to improve infrastructure. In 1986 when I arrived at Davidson College, the office had just been created, consisting of a half-time faculty member and a part-time assistant. Davidson didn't know much about federal funding, but President John Kuykendall and Dean of Faculty Price Zimmerman, as well as his successor Robert Williams, believed the office would be worth the investment. In 1987, Davidson realized its first returns on that investment when five faculty members were awarded grants from the National Science Foundation (NSF), the National Institutes of Health (NIH), and the National Geographic Society totaling about $220,000. (The college was not familiar with indirect costs, so we never asked for any in those grants!)

As Figure 2 illustrates, Davidson's Grants and Contracts Office now is able to secure on the order of $1 million annually for faculty research. The office now has a full-time director, an administrative assistant, and a part-time budget manager for grants. My colleagues at Davidson feel that this was an investment well worth making, as it has eased their burdens of preparing and submitting grant applications, tracking them in the system, and searching out additional opportunities for funding.

Finally, PUIs should pay close attention to how faculty members are rewarded for their research productivity and excellence. Certainly financial rewards for outstanding scientific work should be made part of annual salary increases, but rewards such as release time for grant writing and research, increasing the frequency and availability of sabbatical leaves (for example, implementing full-year sabbatical leaves for particularly meritorious faculty members), or reduced requirements for committee work, to name but a few possibilities, would make a significant impact on a faculty member's morale as she or he pursues cutting-edge research with transformative potential. The last thing any of our institutions need to do is to burn out our most talented and energetic faculty members as they transform science or transform the lives of their students.

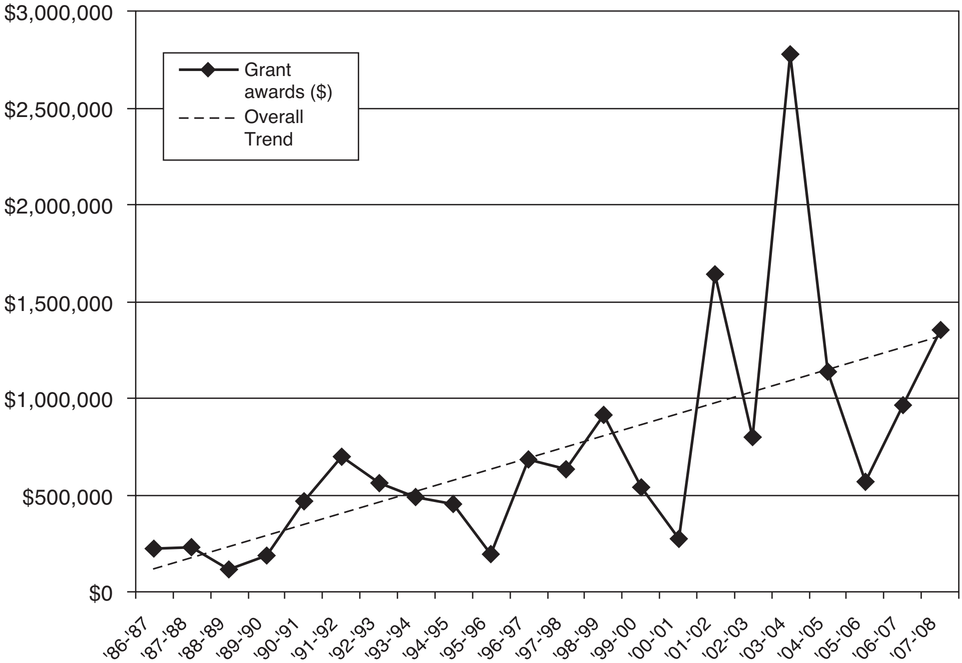

Figure 2. The trajectory of extramural grant awards to Davidson College since academic year 1986-1987. Note that there has been a steady increase in funding as the College maintained its commitment to faculty research by supporting an Office of Grants and Contracts. Faculty hires during this period were characterized by their significant commitment to the integration of teaching and research.

Conclusion

I firmly believe that the talent to conduct transformative research can be found at PUIs, as these institutions bring a diversity and depth of experience to the table. Having a diverse range of institutions contribute to the U.S. research enterprise capitalizes on the wide-ranging talent ready to be tapped in the service of the Nation's scientific and economic goals. It behooves our Nation to use all its resources, particularly during these dire economic times, to enhance our competitiveness in the global marketplace of ideas and technological innovations. Our institutions will ultimately have to decide, campus by campus, whether the investment required to help that talent flourish is valuable enough to the life of the institution to take the financial risk.

To assist PUIs in promoting transformative research, we need to receive significant financial support for research and infrastructure from federal agencies. Clearing the path to such science is too great an effort for PUIs to shoulder alone. Greater federal investment in programs such as the NSF's Research in Undergraduate Institutions, Research Experiences for Undergraduates, and Major Research Instrumentation, as well as the NIH's Academic Research Enhancement Award, would help tremendously. Such investments essentially would make the funding opportunities provided in the recent American Recovery and Reinvestment Act of 2009 a standard part of the science and science-education landscape.

The Howard Hughes Medical Institute (HHMI) provides a model for such efforts; it has done an extraordinary job of transforming the research and education environment at institutions it has supported over the last 20 years through its Undergraduate Science Education Program. The Institute awarded $60 million to 48 liberal-arts colleges and master's-level universities in 2008 alone. Recently, its grants have ranged from a few hundred thousand dollars to $1.6 million per award. Funding of this range to a single institution can radically change how a PUI conducts science and science education and can transform institutions. HHMI's approach is designed to affect every aspect of the biomedical education and research environment at a PUI, from summer research support for undergraduates to postdoctoral support to new faculty hires to significant equipment purchases. A large-scale federal effort cutting across the sciences that emulates HHMI's Undergraduate Science Education Program would be an extraordinary step that would readily position scientists at PUIs—from the social sciences to the natural sciences—to set out on paths of transformative research. It might even help a few of them join the ranks of the gods on Mount Olympus.

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Multiple Approaches to Transformative Research

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Discovery has always been a central tenet of research. For many in the scientific community, the impetus for a research investigation is the quest for understanding and new knowledge. For others, particularly those in fields that are concerned with practice and application (e.g., engineering), fundamental explorations that will yield new technologies, devices, and systems are also considered research. This tension between basic and applied research was eloquently expressed by Vannevar Bush, Director of the Office of Scientific Research and Development, in his seminal report to President Franklin D. Roosevelt in July 1945 (Bush 1945):

> *Basic research is performed without thought of practical ends. It results in general knowledge and an understanding of nature and its laws. This general knowledge provides the means of answering a large number of important practical problems, though it may not give a complete specific answer to any one of them. The function of applied research is to provide such complete answers. The scientist doing basic research may not be at all interested in the practical applications of his work, yet the further progress of industrial development would eventually stagnate if basic scientific research were long neglected.*

Introducing Another Dimension for Research

Vannevar Bush's report, "Science: The Endless Frontier," became the blueprint for scientific research and science policy for many decades. On the fiftieth anniversary of its publication, this philosophy of scientific research was revisited in the three-part conference "Science the Endless Frontier 1945-1995: Learning from the Past, Designing for the Future," organized by Columbia University. At the first session held in December 1994, Donald Stokes, University Professor of Politics and Public Affairs at the Woodrow Wilson School at Princeton University, offered an alternative to the linear model of science as a spectrum from basic to applied research. In his address "Completing the Bush Model: Pasteur's Quadrant" (Stokes 1994), he laid the groundwork for his 1997 book *Pasteur's Quadrant* (Stokes 1997), his title describing the situation in which research is said to be inspired by both a quest for fundamental understanding and consideration of its use. Thus, the one-dimensional continuum ranging from basic research to application is replaced by a two-dimensional view. In Stokes' analysis, a vertical axis addresses the question of whether the research represents a quest for fundamental understanding, and a horizontal axis considers whether the research is inspired by a consideration of use. Pasteur's quadrant, much like the work of Pasteur, exemplifies the interwoven nature of research that is simultaneously practical and basic.

Since the publication of *Pasteur's Quadrant,* other scientists have echoed a call for a "use inspired" research strategy to address societal concerns, national needs, and global challenges. Indeed, the academic sector may be the ideal venue for conducting use-inspired research. At the 2008 Kauffman-Planck Summit on Entrepreneurship Research and Policy, held June 2008 in Bavaria, Germany, the future of the university for the entrepreneurial age was addressed. In his remarks "Building an Entrepreneurial University," Michael M. Crow, president of Arizona State University, described his objective at the university as one seeking "to redefine public higher education through the creation of a prototype solution-focused institution that combines the highest level of academic excellence, maximum societal impact, and inclusiveness to as broad a demographic as possible." (Crow 2008). In describing his paradigm for the New American University, he outlined eight guiding principles, including the following two: "become a force for societal transformation" and "conduct use-inspired research." (Crow 2008) The idea of social embeddedness through use-inspired research aims to measure the value of research by the impact it has on society, especially the regional community around the university.

NSF's Perspective on Research with Societal Impact

The connection between research and society has long been an important element of the vision of the National Science Foundation. For example, in its 1995 publication "NSF in a Changing World: The National Science Foundation's Strategic Plan," the contribution of research to the nation was articulated as a pledge "to provide the stewardship necessary to sustain and strengthen the Nation's science, mathematics, and engineering capabilities and to promote the use of those capabilities in service to society (National Science Foundation 1995)." In this strategic planning document, high-risk research was one of the four themes for investment aimed at helping the NSF "find new ways to encourage its investigators to explore new avenues and pursue activities with high risk and high potential impact (National Science Foundation 1995)." In its fiscal 1999 performance report for the Government Performance and Results Act (GPRA), the NSF noted that it still needed "to improve balance of portfolio by taking more risk in a few programs." (National Science Foundation 2000) The National Science Board (NSB) concurred with this finding and established the Task Force on Transformative Research (Task Force) in December 2004 to examine the policies of the NSF to solicit, identify, and fund innovative, "potentially transformative" research. In the 2007 report "Enhancing Support of Transformative Research in the National Science Foundation," the NSB recommended that NSF "develop a distinct, Foundation-wide Transformative Research Initiative distinguishable by its potential impact on prevailing paradigms and by the potential to create new fields of science, to develop new technologies, and to open new frontiers (National Science Board 2007)." The definition of transformative research now used by the NSF was proposed by the NSB in this document:

> *Transformative research is defined as research driven by ideas that have the potential to radically change our understanding of an important existing scientific or engineering concept or leading to the creation of a new paradigm or field of science or engineering. Such research is also characterized by its challenge to current understanding or its pathway to new frontiers (National Science Board 2007).*

Numerous NSF Paths to Fund Transformative Research

While the NSF's operational definition of transformative research attempts to highlight the uniqueness of these initiatives, the statement does not address the means by which such investigations are catalyzed or conducted. Indeed, there are multiple approaches to achieving potentially transformative results. One way to examine the continuum of avenues for pursuing transformative research is to examine the specific opportunities for receiving funding from the National Science Foundation for such initiatives. An analysis of the funding mechanisms and programs of the National Science Foundation supports the notion that there are numerous paths to potentially transformative advances in science and engineering. Table 1 below highlights seven broad categories of the major funding methods for supporting potentially transformative research at the NSF. These methods include:

- Support through specific NSF programs for exploratory and time-sensitive research, ranging from small scale (e.g., individual) grants (Type I) to collaborative, large-scale efforts (e.g., centers) (Type II);
- Funding in designated high-priority, cross-disciplinary research areas via multi-directorate initiatives, with funding emanating from individual directorates (Type III);
- Awards through the creation of an office within a division either to focus on funding interdisciplinary teams of researchers to address specified emerging frontiers of fundamental research (Type IV) or to support multidisciplinary research via several programs, including some specifically aimed at potentially transformative research areas (Type V).
- Awards through the creation of specific programs (Type VI) or particular divisions within directorates (Type VII) for the purpose of generating proposals that aim to achieve potentially transformative results.

- Awards made for basic research that resulted in high-impact, transformative breakthroughs and advances (Type VIII).

Table 1. Mechanisms for Funding Transformative Research at the National Science Foundation			
Type	**Origin of Idea/ Catalyst of Investigation**	**Mode of Research-Scale and Discipline**	**Formal Programs and Structural Mechanisms for Funding**
I	Emanating unexpectedly from research investigations	Varied, including individual investigator awards	1. Early-concept Grants for Exploratory Research (EAGER) program; prior to 2009 known as the Small Grants for Exploratory Research (SGER) program; 2. Creativity extensions to existing awards; 3. Accomplishment-based renewals to existing grants.
II	Using intellectual synergies from different perspectives to drive discovery. Spawned from collaborations between academic institutions and from the synergies of the discovery-driven culture of science and the innovation-driven culture of industry	Center-based initiatives	Separate programs in seven areas (with year of program initiation and number of centers supported in FY 2008): Centers for Analysis & Synthesis, 1995 (4); Centers for Chemical Innovation, 1998 (9); Engineering Research Centers, 1985 (15); Materials Research Science & Engineering Centers, 1994 (31); Nanoscale Science & Engineering Centers, 2001 (19); Science and Technology Centers, 1987 (17); Science of Learning Centers, 2003 (6).

III	Investments in interdisciplinary activities identified as of high national priority and of greatest scientific opportunity; often supported by multiple directorates; integral to the NSF's mission and vision.	Investigations that cross disciplinary boundaries and require a systems approach to address complex problems and critical needs	Multi-directorate initiatives with cross-directorate management and allocation of funds to each directorate. Thirteen topics selected for major investment in FY 2010, including climate research, cyber-enabled discovery and innovation, cybersecurity, homeland security activities, National Nanotechnology Initiative, and Science and Engineering Beyond Moore's Law.
IV	Selection of frontier topics from comprehensive input from the engineering community on promising future research opportunities that satisfy the criteria of: transformative, addressing a national need or grand challenge, multi- or inter-disciplinary, an area where the community is poised to respond, and clearly demonstrating engineering's leadership capacity.	Collaborations involving one PI (faculty status required) and a minimum of two co-PIs (same or different organizations). Synergistic collaborations with government laboratories, industrial researchers, and scientists and engineers at foreign organizations are encouraged.	Office of Emerging Frontiers in Research and Innovation (EFRI) within the Directorate for Engineering. Topics for which proposals are solicited for FY 2010 are (1) renewable energy storage and (2) science in energy and environmental design: engineering sustainable buildings.
V	Evolving new multidisciplinary research areas arising from advances in disciplinary research to be later integrated into core programs.	Ambitious, large-scale projects involving multiple investigators from multiple disciplines and multiple institutions	Programs within the Emerging Frontiers Office of the Directorate for Biological Sciences. including Assembling the Tree of Life (AToL), Ecology of Infectious Diseases (EID), Frontiers in Integrative Biological Research (FIBR), and Research Coordination Networks (RCN) in Biological Sciences
VI	Seeking new approaches to the deployment of biological knowledge that renders the data and information therein of greater value to the scientific community.	Varied, including individual investigator awards and collaborative multidisciplinary projects	Advances in Biological Informatics (ABI) program within the Directorate for Biological Sciences, with a specific call for proposals that offer potentially transformative outcomes.

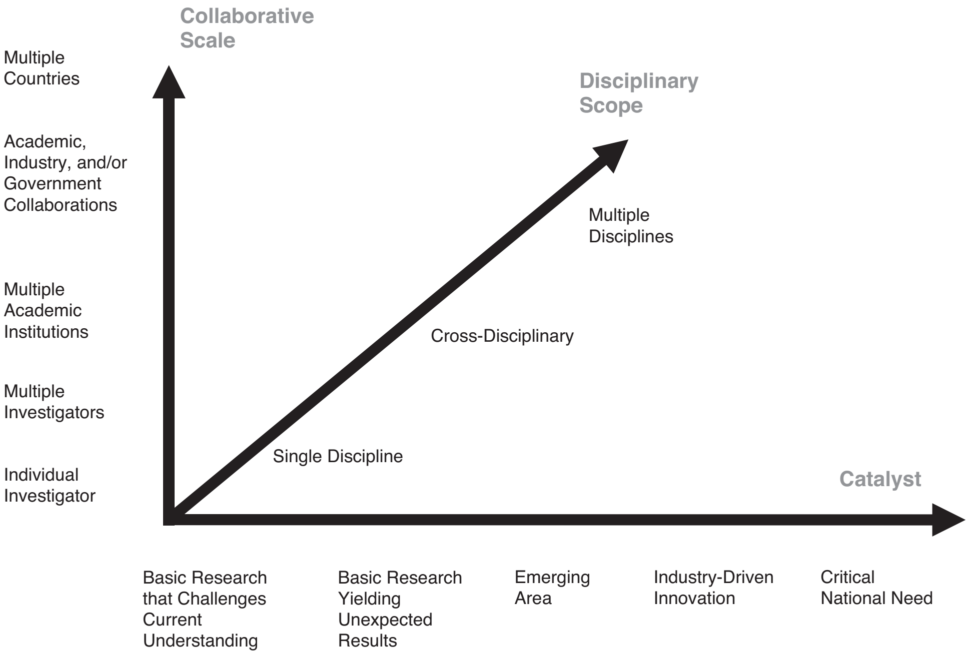

Figure 1. Analysis of Dimensions of Potentially Transformative Research by Catalyst of Idea, Scale of Collaboration, and Disciplinary Scope of Investigation.

VII	Unsolicited proposals submitted to a directorate	Varied, including individual investigator awards and collaborative multidisciplinary projects	High-risk, innovative proposals for fundamental research matching a division's objectives to produce transformative outcomes, such as in the Civil, Mechanical, and Manufacturing Innovation (CMMI) Division of the Engineering Directorate
VIII	Proposal submitted to a directorate for basic research	Varied, including individual investigator awards and collaborative multidisciplinary projects	Conventional peer-reviewed proposals, including CAREER awards

This categorization emphasizes that potentially transformative research can be conducted across a continuum of both scale and discipline via individual investigators, collaborations among investigators within the same institution and/or within the same discipline, and multidisciplinary and/or cross-organizational efforts. Adding a third dimension, the origin of or catalyst for the idea might be rooted in basic research that challenges prevailing paradigms at the outset; might emanate from basic research that yields unexpected and/or significant findings; might be foreseen as an emerging area of research and innovation; might arise

Characterization of a Novel Sub-ice Shelf Antarctic Cold-Seep Ecosystem Michael McCormick, Associate Professor of Biology, Hamilton College

In 2002 a large portion of the Antarctic Larsen B IceShelf disintegrated, permitting the first opportunity to explore the underlying ocean floor. In 2005, a colleague in the geosciences department, Gene Domack, conducted the first survey of this area and recorded video evidence of a novel cold-seep ecosystem located well within the bounds of the pre-existing ice shelf. Cold seeps are areas in which hydrocarbons (principally methane) or hydrogen sulfide seep up through the ocean floor. In the absence of light, primary production in cold seeps is dependent upon chemoautotrophic prokaryotes. The presence of large clams in the video survey of the Antarctic cold seep indicated that this ecosystem was established many years before the ice-shelf collapsed. Given that organic inputs were likely severely limited while the ice-shelf was intact, we are trying to understand how sufficient carbon and energy could be delivered to support this ecosystem. We hypothesize that glacial reworking of petroliferous shales underlying the cold-seep basin has provided hydrocarbons that support methanogenesis at this site. If correct, this would imply that many other cold seeps could exist in similar geologic settings under the extant Antarctic ice-shelves, which cover 1.5 million kilometers, a geographically significant feature of our planet comparable in size to the Sahara desert.

Given the urgency of characterizing this ecosystem before the original structure was obscured, I sought and received an NSF SGER to sample site in the spring of 2006. Unfortunately, we were unable to access the site due to bad ice conditions. Subsequently, I was awarded a second NSF grant to return to the site in 2010 (from the Office of Polar Programs, International Polar Year Program). This second proposal is a larger, multi-PI effort that will expand the scope of our sampling to include macrofaunal and megafaunal components of the seep community. No undergraduates will participate in the research cruise, but summer-research students and senior-thesis students will participate in subsequent analyses of returned samples.

from synergistic drives from academics and industry; or might be prompted by critical national needs. Figure 1 captures the essence of this analysis, with potentially transformative research characterized by any point in this three-dimensional space.

Examples of Transformative Research at Predominantly Undergraduate Institutions

As illustrated in the sidebars throughout this chapter, the examples of potentially transformative research involving faculty and undergraduate students at predominantly undergraduate institutions exemplify the array of funding mechanisms.

For example, the project "Characterization of a Novel Sub-ice Shelf Antarctic Cold-Seep Ecosystem," conducted by Professor Michael McCormick at Hamilton College, is an endeavor originally supported by the National Science Foundation's Small Grants for Exploratory Research (SGER) program (Type I) and subsequently funded by the Division of Antarctic Sciences in the Office of Polar Programs as part of the NSF-wide investment in the International Polar Year 2007-2008 (Type III). This large-scale international effort involving multiple investigators aims to examine the profound transformation in ecosystem structure and function that is occurring in coastal waters of the western Weddell Sea, as a consequence of the collapse of the Larsen B ice shelf. The SGER program was designed to support exploratory and high-risk research characterized as either "preliminary work on untested and novel ideas; ventures into emerging research ideas; the application of new expertise or new approaches to 'established' research topics; research having extreme urgency with regard to availability of or access to data, facilities, or specialized equipment, including quick-response research on natural disasters and similar unanticipated events; and efforts of similar character likely to catalyze rapid and innovative advances (National Science Foundation 2002)." In January 2009, NSF announced that the SGER program would be replaced by two programs: Grants for Rapid Response Research (RAPID) and Early-concept Grants for Exploratory Research (EAGER). RAPID is described as a funding mechanism to support "quick-response research on natural or anthropogenic disasters and similar unanticipated events. (National Science Foundation 2009)" It seeks proposal for one-year grants for a maximum budget of $200,000; proposals will be reviewed internally. The EAGER mechanism supports "high-risk, exploratory and potentially transformative research. [9]" It will fund two-year grants of up to $300,000 and for a two-year duration.EAGER proposals also will be reviewed internally at NSF.

Faculty members at predominantly undergraduate institutions are conducting transformative research with funding from the Civil, Mechanical, and Manufacturing Innovation (CMMI) Division of the Engineering Directorate of the National Science Foundation (Type VII). For example, Professor Kellar Autumn from the biology department at Lewis & Clark College is pursuing a research project on "Gecko-inspired Adhesion Technology" through

Gecko-inspired Adhesion Technology
Kellar Autumn, Professor of Biology, Lewis & Clark College

Gecko toes bear dry, self-cleaning, mechanically controllable adhesive nanostructures. Engineered nanostructures inspired by geckos may become the glue of the future. In our initial NSF-funded project, we focus on identifying general, testable principles of gecko adhesion, in the hopes of enabling transformative advances in adhesion technology and in our understanding of the fundamental nature of friction. Recent results suggest that geckos, atoms, and earthquakes have common dynamics. In a subsequent investigation supported by NSF, we focus on dry self-cleaning by studying electrostatic, van der Waals, and liquid-adhesion effects using natural and synthetic nanofiber arrays. We will integrate passive mechanical properties and electrical actuation of nanofibers to create smart surfaces to selectively collect or remove particles. The research will advance the development of smart, self-cleaning adhesives for applications such as electrical interconnection, particle capture/removal, biocompatible, reusable adhesives, and climbing robots. The projects include four undergraduate researchers per year and development of five K-12 teaching modules and a Lego Robotics version of our two-dimensional dynamic micro-tester.

Some of our recent publications with undergraduate co-authors include Autumn, Kellar, Metin Sitti, Yiching A. Liang, Anne M. Peattie, Wendy R. Hansen, Simon Sponberg, Thomas W. Kenny, Ronald Fearing, Jacob N. Israelachvili, and Robert J. Full. 2006. Evidence for van der Waals adhesion in gecko setae. Proc. Natl. Acad. Sci. 99: 12252–6. Also see the cover article Autumn, Kellar. 2006. How gecko toes stick. American Scientist 94: 124-32.

Extending the RAST Server to Support Reconstruction and Modeling of Cellular Networks Nathan Tintle[1], Aaron Best[2], and Matt DeJongh[3]
[1]Department of Mathematics, [2]Department of Biology, and [3]Department of Computer Science, Hope College

We are working to extend the RAST server, a free, Web-based genome-annotation service widely used to store data on the greatly increasing number of sequenced organisms, to support three additional types of analyses: (1) generation and refinement of genome-scale metabolic reaction networks, (2) genome-based prediction of transcriptional regulons, and (3) analysis of gene-expression microarray data and regulatory-network prediction. These tools will enable RAST users to perform iterative cycles of analysis, successively refining an integrated knowledge base about an organism's transcription, regulation, and metabolism. This effort will provide capability for potentially transformative systems-level analysis for hundreds of bacterial and archaeal genomes. This research effort is coordinated by the PIs at Hope College and two other institutions, who lead an international team of researchers. The team also includes eight undergraduates at Hope. The research is supported by a $1.2 million Advances in Biological Informatics grant from the National Science Foundation.

an NSF grant. Professor Alex Small in the physics department at California State Polytechnic University—Pomona is pursuing research on the topic of "Optics Beyond the Diffraction Limit," supported by the National Science Foundation through a collaborative grant with an investigator at the University of California-Berkeley.

With NSF funding from the Advances in Biological Informatics program within the Biology Directorate (Type VI), Professors Nathan Tintle, Aaron Best, and Matthew DeJongh, all of Hope College, lead a collaborative international team of investigators to extend the Rapid Annotation using Subsystem Technology (RAST) genome-annotation server to support reconstruction and modeling of cellular networks. Their work focuses on the development of software tools to enable three types of analyses that will be integrated into the RAST server: (1) generation and refinement of genome-scale metabolic reaction networks; (2) genome-based prediction of transcriptional regulons; and (3) analysis of gene-expression microarray data and regulatory-network prediction. The extended RAST server will provide the bioinformatics community with an integrated array of sophisticated tools that enable rapid, high-quality, and efficient analyses of large-scale, genome-based data sets.

Investigators at PUI campuses are also involved in the ambitious Assembling the Tree of Life (AToL) program, within the Emerging Frontiers Office of the Directorate for Biological Sciences, including a Type V award. For example, a collaborative effort to investigate Cnidarian phylogeny includes Professor Catherine McFadden of the biology department at Harvey Mudd College. While members of the phylum Cnidaria often have quite simple anatomy (e.g., marine fauna such as corals, sea anemones and jellyfish), cnidarians have attained incredible diversity with more than 11,000 species. This project will obtain DNA sequencing data from 1,800 cnidarian species, generating approximately 23 million base

Assembling the Tree of Life: Cnidaria
Catherine McFadden, Department of Biology, Harvey Mudd College

Phylum Cnidaria comprises more than 11,000 described species, which include a few freshwater species and prominent members of marine fauna such as corals, sea anemones, and jellyfish. The objective of the Cnidaria AtoL (CnidTol) is to enhance our understanding of the evolutionary history of the phylum, one of the earliest branches in the animal tree of life. Morphologically simple, with relatively few cell types, cnidarians have attained remarkable diversity through modifications, largely in colonial organization and life histories. The dichotomy between simple cellular and tissue organization and diverse form and life history has contributed to long-standing controversies concerning the origin and diversification of cnidarians. Reconstructing the cnidarian evolutionary tree is important for understanding the patterns and processes that accompanied the early diversification of animals.

This research is being conducted by investigators from seven colleges and universities and the Smithsonian Institution, with a grant from the National Science Foundation's Assembling the Tree of Life Program. Two of the participating institutions are liberal-arts colleges, and undergraduates play a significant role in the project.

pairs of cnidarian DNA sequences, which will be used to reconstruct cnidarian phylogenies (evolutionary trees) using computer algorithms and supercomputing facilities. Reconstruction of a cnidarian evolutionary tree will enhance our understanding of the patterns and processes that accompanied the early diversification of animal life.

Many faculty members at PUIs are conducting potentially transformative research through conventional funding mechanisms at the National Science Foundation (Type VIII). Professor Andrea Lommen at Franklin and Marshall College received a five-year NSF CAREER grant to support her work aimed at detecting gravitational waves via pulsar timing. This work not only could potentially transform the field of astrophysics, but also will likely contribute to additional significant scientific advances, including increased understanding

Detecting Gravitational Waves via Pulsar Timing
Andrea Lommen, Department of Physics and Astronomy,
Franklin and Marshall College

At Franklin and Marshall College, Professor Andrea Lommen is engaged in the search for gravitational waves, the discovery of which is likely to happen in the next decade and will transform the field of astrophysics. Gravitational waves are a fundamental perturbation in space-time and have the potential to allow us to understand the most enigmatic events in the universe—including the formation and mergers of galaxies, the formation and spin of black holes, and the equation of state of neutron star matter. The work is supported by a five-year NSF CAREER grant awarded to Lommen in 2008. She leads the North American NANOHertz Observatory of Gravitational Waves (NANOGrav), an organization dedicated to detecting gravitational waves via pulsar timing. Combined with other NANOGrav member institutions, most notably Bryn Mawr College, Oberlin College, the University of Texas Brownsville, and West Virginia University, between 10 and 20 undergraduates are involved every year.

Optics Beyond the Diffraction Limit
Alex Small, Department of Physics, California State Polytechnic University, Pomona

This research involves theoretical studies of new techniques for beating the diffraction limit in fluorescence microscopy of living cells. Recent experiments have shown that special fluorescent molecules enable microscope images with resolution far better than the wavelength of light (previously regarded as the fundamental resolution limit). With new experiments overturning theories established by Abbe and Rayleigh, we are formulating a new theory of resolution and speed limits. Intriguingly, we find that the fundamental limits arise not from instrument performance but rather the algorithms used to analyze the images. This theory will transform our understanding of microscope resolution and lead to computational tools for obtaining molecular-scale images of cells. This work involves undergraduates and is supported by internal sources and Research Corporation. A recent collaboration involves Dr. Keith Lidke (University of New Mexico).

of the interstellar medium; increased understanding of constraints on populations of various sources of gravitational waves, such as binary massive black holes and cosmic strings; an increased number of known pulsars; increased precision in timing pulsars; improved solar-system ephemerides; and improved knowledge of the energy density of the stochastic gravitational wave background.

Recent work by Professor Alex Small in the Department of Physics at Cal Poly Pomona has shown that the diffraction limit in fluorescence microscopy of living cells can be overcome by a variety of techniques. His work demonstrates that the wavelength of light is no longer the fundamental diffraction limit. Using techniques such as STOchastic Reconstruction

Identification of Natural Products to Confer Protection against the Chytrid Fungus
Kevin Minbiolem, Department of Chemistry and Biochemistry, and
Reid Harris, Department of Biology, James Madison University

The class Amphibia faces a crisis, with at least 33 percent of the species considered vulnerable to extinction. This is partly due to chytridiomycosis, a skin disease caused by the fungal pathogen Batrachochytrium dendrobatidis (Bd), which decimates many amphibian populations and yet spares others. We have hypothesized that cutaneous, mutualistic bacteria play a role in amphibian resistance. To this end, our NSF-sponsored research has identified anti-Bd metabolites from bacteria on salamanders' skin. Furthermore, we have shown that exposure to protective bacteria before Bd infection improves the health and survival of multiple amphibian species; this was linked to anti-Bd metabolite production. Exploitation of cutaneous bacteria and their metabolites may provide long-term resistance to Bd and serve as a model for managing future emerging diseases in other wildlife populations. This work has been carried out by the Departments of Chemistry and Biology at James Madison University, with work done by ~10 undergraduates and two masters students.

Sixty students have been involved in this research over the last five years. The Harris/Minbiole research was presented on "The Vanishing Frog" on Animal Planet in November 2008.

The Firefly Satellite Mission: Understanding Earth's most Powerful Natural Particle Accelerator
Allan T. Weatherwax, Department of Physics & Astronomy, Siena College
Doug Rowland, Space Weather Laboratory, NASA Goddard Space Flight Center

Lightning discharges represent the release of enormous amounts of energy and are associated with familiar and powerful manifestations near the earth's surface: thunder, a bright flash, and a powerful current that can shatter trees and turn sand to glass. Lightning may also give rise to x-ray and gamma-ray bursts, and, unlike the well-known flashes of light and claps of thunder, these energetic rays are channeled upward and can be detected only from space. A new CubeSat satellite mission, called "Firefly," sponsored by the National Science Foundation, will explore the relationship between lightning and these bursts of radiation called terrestrial gamma ray flashes (TGFs). TGFs are of inherent interest, as they result from the most powerful natural particle-acceleration process on earth, in which thermal electrons are energized to tens of millions of volts in less than a millisecond. By studying TGFs, we can learn fundamental physics critical in understanding not only lightning, but also solar flares, cosmic shocks, and even dust storms on Mars. Firefly is a small satellite (4.0 kg, 10x10x34 cm), that will be designed, built, tested, and operated in orbit as part of this project. The Firefly team is a collaboration between Siena College and NASA, with the Hawk Institute serving as the spacecraft bus provider. Students will be involved in all aspects of the project, from design and development to mission operations and data analysis.

Microscopy (STORM) and STimulated Emission Depletion (STED), he has achieved images of cells with resolution of 40 nanometers or better.

Professors Kevin Minbiole of the department of chemistry and biochemistry and Reid Harris of the biology department at James Madison University have been supported by numerous NSF grants in their explorations of the role of bacteria on amphibian skin that protect amphibians from a lethal fungal disease caused by the fungal pathogen Batrachochytrium dendrobatidis. Their research provides important information to ongoing and crucial conservation efforts of frog and salamander populations and was featured on "The Vanishing Frog," a show on the Animal Planet network in November 2008.

Professor Allen Weatherwax of the department of physics and astronomy at Siena College is engaged in NSF-sponsored collaborative research with colleagues at NASA's Goddard Space Flight Center and the Hawking Institute to definitively determine whether terrestrial gamma ray flashes (TGFs) are produced by lightning. The study also is aimed at determing-ing the characteristics of lightning that produce the fluxes of gamma rays observed at high altitude. By studying the TGF phenomena and the acceleration processes responsible for them on earth, the investigators will improve understanding of other regimes of electron acceleration, including the radiation belts, solar flares, cosmic shocks, and will gather planetary information on Venus, the outer planets, and dust devils and dust storms on Mars. As part of this project, the Firefly CubeSat satellite will be designed, built, tested, and operated in orbit.

Soliciting Potentially Transformative Research Proposals

The National Science Board recognizes that despite the multitude of mechanisms for funding potentially transformative research at the National Science Foundation, these mechanisms do not ensure that such proposals are received or funded (National Science Board 2007). Indeed, one of the prevailing perceptions in the research community is that the NSF does not support transformative research. A 2007 survey of reviewers and submitters of NSF proposals was designed to study in detail the trends, impacts, and causal factors associated with NSF proposal funding and submission rates (National Science Foundation 2007). Survey respondents revealed that:

- 61.5 percent believed that fewer than 10 percent of the proposals that they had reviewed in the last three years constituted transformative research; 84.6 percent indicated that fewer than 25 percent of the proposals involved transformative ideas;
- Only 21.9 percent of the reviewers felt that the NSF programs for which they had reviewed proposals greatly welcomed transformative research;
- Only 14 percent of the review panels on which respondents served welcomed transformative research to a great extent and only 10 percent of the panels' reviewers frequently recommended transformative research proposals for funding;
- Only 13.7 percent of proposal submitters believed that the NSF tends to fund transformative research proposals to a significant degree;
- Nevertheless, 45.1 percent would submit their transformative research ideas to the NSF.

This analysis of multiple approaches to potentially transformative research has emphasized the role of the National Science Foundation in soliciting, identifying, and funding such initiatives. Indeed, the NSF recognizes that "transformative research can arise in different forms" and that "multiple parallel approaches" of NSF support are needed to promote transformative research (National Science Board 2006). Certainly other federally funded entities (e.g., the Department of Energy, National Institutes of Health, etc.) and a number of private foundations also support potentially transformative research. Thus, those in the undergraduate research community will find that federal and private funding sources provide a variety of means to catalyze innovative thinking and to challenge current understanding that will lead to potentially transformative research.

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Using Transformative Research to Enrich Science Curricula and Enhance Experiential Learning

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The term transformative research (TR) describes a range of innovative endeavors that promise extraordinary outcomes. TR must, by definition, revolutionize entire disciplines, create entirely new fields, or disrupt accepted theories and perspectives (National Science Board, 2007). In other words, such research has the potential to change the way we address challenges in science and engineering. By reframing the way we approach the challenges basic to our disciplines, TR implicitly reframes pedagogy. While transformative research can be rapidly disseminated among a cohort of active researchers, teaching resources tend to evolve much more slowly, resulting in a disconnect between how science is done and how it is taught.

New initiatives by many of the nation's most prominent public and private funding agencies (e.g., the National Science Foundation, the National Institutes of Health, the Howard Hughes Medical Institute, Research Corporation, and the American Chemical Society Petroleum Research Fund) make transformative research a funding priority. The goal is to foster creative, high-risk, but potentially high-payoff research, countering the relatively measured and safe research that has emerged as funds for such work have diminished. This new focus is driven by two major factors: First, there is an increased awareness that the problems we face in the twenty-first century can only be solved with fresh ideas, ideas that often require unexpected combinations of diverse disciplines. Second, there is a growing awareness that if the United States is to remain a leader in research and development, we must facilitate such research. Funding initiatives that stress creative leaps over incremental advances are the major stimuli for challenging the status quo in current research in order to address our perceived needs.

Given the technical sophistication and pace of research in science and engineering, it may seem that scientists operating research programs at primarily undergraduate institutions (PUIs) in collaboration with undergraduates, instead of well-trained postdoctoral students, will be excluded from the competition for funding for transformative research. However, we believe that exactly the opposite can and should be the case. Many potential benefits can arise from shifting the research focus at PUIs away from incremental projects that advance knowledge slowly and produce some minimal publishable unit, towards more ambitious projects that have the potential to be transformative. Further, we propose that an emphasis on transformative research will be equally transformative for science curricula, helping to recruit the best and brightest students to careers in science and better preparing them to approach the complex problems we are facing in the world.

Innovative Undergraduate Training Through Transformative Research

The National Academies of Science's 2007 publication *Rising Above the Gathering Storm* presents data suggesting that an inadequate number of students choose science, mathematics, and engineering as fields of study. It also asserts that the globalization of the world's economy creates new problems, including the urgent need to ensure economic well-being, promote public health, and protect the earth's limited resources and environment (National Academy of Sciences, 2007). As researchers, we must step back from habit and tradition to look for revolutionary new ideas and technologies to best address these problems. Perhaps more importantly, as educators we must recognize that the next generation of scientists and engineers cannot be effective by practicing the old approaches of the twentieth century. In short, innovation needs to become the rule rather than the exception if we are to keep pace with changing and challenging times.

Science education has always been driven by an evolving base of knowledge, but the pace of advances in the life sciences, combined with significant developments such as the sequencing of the human genome, has entirely remapped the research frontier. The post-genomic era has led to a call for new training that not only enables students to practice as scientists (e.g., Handelsman et al., 1997; Handelsman et al., 2004; Hanauer et al., 2006), but that also fosters innovation (DeHaan, 2009) and collaboration (Tanner et al., 2003). Part of the challenge in renovating our science-education curriculum is developing new ways to enable mastery of material that is critical to practice in the discipline, without drowning in the massive volume of accumulated knowledge (Wood, 2009). Liberal-arts curricula already excel in teaching critical thinking and creativity (Kuh, 2007), so scientists working at PUIs are poised not only to participate in transformative research, but also to incorporate those ideas into science education.

Higher education in general is moving toward high-impact engagement with real-world problems for students, incorporating transformative research, including community-based and other forms of experiential learning (Barr and Tagg, 1995; Boyte and Farr, 1997; Cantor, 1997; Karukstis, 2005). Focusing on TR offers all the advantages of integrating research into the curriculum (see Osborn and Karukstis, 2009). It stimulates greater student engagement, enhances learning of content, and emphasizes the active synthesis of classroom knowledge. In the context of a small, undergraduate-focused institution, participation in TR offers additional benefits (National Survey of Student Engagement Advisory Board, 2007). Perhaps the most important of these benefits is that collaboration with undergraduates on potentially transformative research projects exemplifies current "best practices" in education (Fink, 2003). Collaborating with undergraduates on TR goes beyond being problem-based, by offering an intellectual edge that emphasizes experimental strategy. In addition, because research and teaching are so closely intertwined at PUIs, the dissemination of cutting-edge knowledge in the classroom is likely to happen very quickly, as faculty members identify gaps in the knowledge presented in textbooks and develop active-learning projects to fill such gaps.

TR in an Undergraduate Curriculum

In order to bring TR to an undergraduate institution, that institution must create an environment and academic culture that encourages and stimulates its development. The administrative perspective is dealt with in other chapters, but for faculty members, the challenge is reconciling the potentially competing pressures between effective research and teaching programs. At one extreme end of the spectrum of possibilities, it might be tempting to take advantage of the off-the-rack teaching materials that accompany textbooks to free space and time to develop a creative research program. Alternatively, it might be efficient to design research projects that can allow faculty members to publish relatively short, narrowly focused papers, creating more time to develop innovative teaching. TR can bridge the teaching and research missions. Simply tuning in to current literature and funding initiatives helps foster an intellectual readiness to expose students to new case studies, as well as to inspire new contexts for faculty members' research programs. Maintaining currency with the literature simultaneously helps faculty members keep their teaching up to date and increases the probability that their research pursuits will contribute to the nation-wide need for science that sees the forest for the trees.

Individual faculty members can be "change agents" to promote an environment conducive to TR, but faculty at PUIs face several challenges to remaining current with the literature that are different from the challenges faced by colleagues at larger research institutions. Universities and research institutes typically offer regular seminars that invite leaders from all fields to talk about their current work. Faculty members at PUIs must rely on other sources to maintain currency. With a significant teaching load, there isn't time for exhaustive literature reviews. Fortunately, advances in technology enable very efficient strategies that help busy faculty members prioritize research goals and identify significant papers as they are published. For example, funding agencies send email alerts that announce new funding initiatives, and most journals will send email summaries of their tables of contents. A scientist can identify the top five journals in his or her field and get on those free lists. Also, there are subscription services that help identify top papers in an area, and memberships in professional societies provide access to current scholarship. In biology and medicine, for example, a subscription to the "Faculty of 1000" will identify what established experts in an area believe are the major recent publications in their discipline. The American Society of Cell Biology's newsletter has a "hot paper" column. Free publications such as *The Scientist* send email announcements that give new highlights and can be quickly scanned.

There are advantages to the environment at PUIs that can help to integrate TR into the laboratory and the curriculum. The nature of teaching at a PUI helps to maintain breadth of knowledge, as most professors teach survey courses or offer electives on topics other than their own research specialties. This breadth lends itself naturally to classroom discussions about big ideas and the broad challenges facing the world. It takes only a small shift in focus to apply that kind of integration to research questions that could be transformative. Similarly, research programs at PUIs capitalize on the energy and enthusiasm of undergraduates. There are many examples of seminal research breakthroughs made in collaboration with undergraduate researchers (e.g., Andrew Huxley's contributions to understanding the biophysical basis of the action potential in neurons, http://nobelprize.org/nobel_prizes/medicine/laureates/1963/huxley-bio.html). Undergraduates approach research problems with a fresh perspective, unencumbered by tradition and the vast literature that came before. Who better to accompany a researcher on a journey into TR than the open-minded and active young scholars who fill our undergraduate classes?

Introducing undergraduates to transformative ideas early in their educational experience will help them become excited about the frontiers of science and will enable them to be more comfortable working at those frontiers as they embark on research. Thus striving to conduct TR has the potential to invigorate the curriculum, not only by creating unique research opportunities, but also by introducing novel ideas into existing classes and creating new courses or programs. Just as we take an experimental approach in our research, so also will we begin to experiment in the classroom, leading to direct benefits for faculty, students, and the curriculum at large.

TR's Benefits for Faculty

There is no question that striving to do transformative work requires commitment from the faculty member beyond what it takes to produce incremental research progress on a well-established problem. Taking on research projects that have the potential to be transformative can inject currency and vibrancy into a research program, but such projects do involve additional risk, particularly for pre-tenure faculty. These projects might not pay off or they may take longer to get publishable results. Yet we would argue that pushing oneself to think more broadly than the obvious next step and deliberately developing projects that have transformative potential is likely to have many benefits. As faculty members develop potentially transformative ideas, they will need to be up to date on the relevant scientific literature, network with scientists at other institutions and in other disciplines, develop collaborations, and initiate new research projects. They may even need to learn new techniques and paradigms. How can these activities be anything but beneficial? Further, if the research is to be transformative, it must address a significant problem, and that is exciting. Engaging in exciting science is easy to convey in writing grant proposals, and because TR is in line with current missions of funding agencies, the chances of obtaining support for the proposed research will be higher.

Deliberate planning to bring TR into a research program provides an opportunity to evaluate one's entire research agenda. Such critical reflection should strengthen the range of projects that are being conducted in a faculty member's lab, shifting the balance in research planning toward a creative endeavor rather than planning where to place the next brick in the wall. TR ensures that even the bread-and-butter projects in the lab move forward to address important questions, rather than following the next obvious step. Even if, in the end, the primary research plans follow a linear path, that research is likely to be better for the elevated enthusiasm of the investigator, and for critical consideration of what the project means in the context of big questions.

TR's Benefits for Students

The benefits to students are also likely to be many, ranging from the practical experience of working on a problem with transformative potential to more general benefits that come from being exposed to transformative ideas. Experiential learning in and of itself is often transformational for students (Kolb and Kolb, 2005; Handelsman et al., 2007; Fairweather, 2008). In this regard, research is no different from any other form of experiential learning (Osborn and Karukstis, 2009). It gives students an opportunity to practice in their field of interest and offers them the potential to make a novel contribution to the field. Beyond these well-established benefits, experience with potentially transformative research offers the added benefit of developing skills in creativity and practice in generating new knowledge. In science education, these skills extend beyond the traditional criteria for learning that begin with knowledge recall and culminate with analysis, synthesis, and evaluation (Bloom, 1956).

Finally, from a training perspective, a chance to work on an ambitious, potentially transformative project or to be introduced to such ideas in the classroom, offers an unparalleled advantage for undergraduate science students to develop the creative skills they will need to generate the next set of transformative ideas. Current science training is arguably antithetical to creativity. It emphasizes analytical, purposeful thought, focused on cause and effect, and disciplined through the exclusion of divergent ideas. In contrast, current views on what stimulates creativity emphasize "associative richness"—thinking that is "defocused" and intuitive (Gabora, 2002; Simonton, 2004). When the professor is engaged by transformative ideas, he or she provides a model for creativity that can help students practice generating their own innovative ideas (DeHaan, 2009). Beyond this, TR puts undergraduates in the midst of intellectual ferment. Evidence shows that direct interactions with faculty members, both in the classroom and in research, contribute significantly to the student's educational experience (Umbach and Wawrzynski, 2004). Undergraduates are passionate about new ideas (especially ideas relevant to "real world" problems such as the environment or public health), and they will devote a tremendous amount of energy to ideas that excite them.

TR's Curricular Benefits

There is a significant time lag between scientific advances and their incorporation into textbooks; transformative ideas without accompanying data may not appear at all. Focusing on TR within one's scholarship necessarily invokes current ideas and creates a culture of "positive restlessness" (Kuh et al., 2005). If encouraged to bring this restlessness to the classroom, both faculty members and students will grapple with stimulating new data and explore creative solutions to important, real-world problems. Focusing on new ideas, current problems, and potential solutions, in turn, can be brought from the classroom back into the research lab, creating a productive and exciting cycle of learning that benefits a faculty member's scholarship and teaching equally. If the professor is working on big problems similar to those discussed in class, those problems seem more approachable and less lofty for the students.

The curriculum could be significantly influenced both in terms of course content and through the development of entirely new courses. Some of these changes might be influenced directly by the immediate research topic that the faculty member is working on. But it is also likely that simply being on the lookout for transformative ideas will lead a professor to other innovative concepts, and in turn, to weave those concepts into his or her program of study. Students can be exposed to ideas that might be "revolutionary," but still under investigation. For example, a collaboration across the disciplines of psychology, neuroscience, education, and machine learning may lead to a complete transformation of our understanding of teaching and learning (Meltzoff et al., 2009). This "new science of learning" recognizes that social interaction is a pre-requisite to the acquisition of many new concepts and skills (e.g., speaking a foreign language) and includes ideas about the utility of incorporating "social robots" (that is, machine-based tutors that are programmed to have social skills) into the classrooms of the future. These ideas are still in the developmental stage, but faculty members across a broad array of disciplines who are interested in research on teaching and learning can bring such theories into the classroom conversation and into their own potentially transformative work. After being exposed to radical new ideas (e.g., future classrooms filled with social robots), the students themselves will begin to discover how to ask the kinds of questions that advance the state of the science.

In the life sciences, new techniques can transform the state of the field. The sooner students are introduced to these techniques, and the data that come from their implementation, the better. Conceptual introduction in the classroom is vital, but hands-on experience in teaching laboratories is likely to be equally important for students to appreciate how these advances work. One example is efforts to introduce state-of-the-art genetics tools and then to relate them to real-world problems in introductory science courses (http://www.hhmi.org/coolscience/resources/SPT--FullRecord.php?ResourceId=106); another is to develop new inquiry-based projects that bring genomics tools to the curriculum (e.g., "Teaching Big Science at Small Colleges" http://serc.carleton.edu/genomics/index.html, a collaborative project sponsored by the Teagle Foundation). A similar project recruited undergraduates to participate in the sequencing and annotation of microbe genomes, not only involving the students in ground-breaking techniques, but also including some of them as coauthors on high-profile publications (Goodner et al., 2001; Forst and Goodner, 2006; Goodner and Wheeler, 2006). Other transformative tools that are changing the life sciences include advances in live cell imaging (see a special issue of *Science* in 2003 devoted to biological imaging) and nanobiotechnology (Craighead, 2000; Whitesides, 2003). Both of these approaches merge technological developments in engineering and physics with current problems in biology.

Bringing such topics to the classroom necessarily fosters cross-disciplinary teaching, encourages research collaborations among faculty members from different fields, and produces vital training for future scientists (Withers and Wallace, 2007). The nanobiotechnology course offered through the NSF's Nanobiotechnology Center, for example, spans several universities and puts engineers and biologists in the same virtual room, where they struggle to speak each others' language. By the end of the course, however, discipline-spanning teams have learned how to collaborate through brainstorming, leading to the development of novel nanofabrication projects to address biological problems (see sample course syllabus at http://www.nbtc.cornell.edu/edu_course.htm). Brainstorming, originally developed for advertising (Osborn, 1948), has become a powerful tool for teaching creativity and problem-solving in science, as well as in other disciplines (Miller et al., 2008; DeHaan, 2009).

Researchers at PUIs are Suited for TR

Clearly, engaging in TR involves a certain amount of risk-taking. After all, "ninety-nine percent of the discoveries are made by one percent of the scientists" (Julius Axelrod, Nobel laureate), and often one's research program is not defined as "transformative" until many years after its completion. Are the risks associated with TR too great for faculty members who divide their time between the classroom and the research lab? Or, as we believe, are teacher-scholars perfectly poised to embrace this risk and to take full advantage of the opportunities to make radical changes in their research fields?

To better understand why faculty members at PUIs may be uniquely prepared to take on TR projects, consider the basic human tendency to be risk-averse. When faced with uncertainty (e.g., Will my inventive hypotheses be supported by the data? Will a granting agency fund this project?), one's natural inclination is to avoid risk and embrace, instead, certainty (such as continuing a well-established line of research). As Daniel Kahneman, a Nobel-Prize-winning economist, and Amos Tversky, a psychologist, have illustrated, potential losses loom much larger than potential gains when one faces risk or uncertainty (Kahneman and Tversky, 1984; Tversky and Kahneman, 1991; Tversky and Kahneman, 1992). That is, we are particularly sensitive to the idea of losing something that we already have.

In one experimental demonstration by Kahneman and colleagues, half of the participants were shown a coffee mug and asked how much they would pay for it. The other half were told the mug was theirs to keep and later were asked how much they would be willing to sell it for. The discrepancy between the two sets of figures was tremendous. Those who had been given the mug (and for whom loss loomed larger) demanded more than twice as much money for the mug as the other participants were willing to pay (Kahneman et al., 1990). This robust phenomenon, called the endowment effect, highlights how the perceived value of an object changes depending on whether or not it is already in our possession. Indeed, aversion to loss helps to explain why people are so much more comfortable with the status quo than they are with change, especially when change includes risk (Kahneman et al., 1991).

Thus, for example, consider an accomplished, well-respected scholar at a major research university who has had great success pursuing a particular line of research. If this scholar uses grant funding to support a number of graduate students and post-docs and routinely includes these trainees on publications in order to enhance their chances of career advancement, she may be (understandably) hesitant to reallocate some of her time and energy to an unproven, risky research project. This researcher has a great deal to lose (as do her graduate students and post-docs!), because her reference point is what she already "has" (a successful graduate training model, grant funding, institutional support). Faculty at PUIs are less likely to have a cadre of graduate and post-doctoral student collaborators dependent on their predictable grant funding and publications. So when faculty members at PUIs consider engaging in TR, what looms large is not the potential for loss (i.e., of funding, of graduate students' success), but rather the potential for gain (of accomplishing something extraordinary, of unique opportunities for undergraduates, of a more vibrant curriculum). Having a reference point that grounds a researcher in the potential gains rather than in the potential losses makes TR a relatively attractive gamble for PUI faculty members and their undergraduates.

The Leap of Faith

In principle, the advantages of striving for transformative research are clear. The potential gains for the educational curriculum and for personal development as a teacher-scholar outweigh the risks of not producing transformative findings. A recent white paper from the Teagle Foundation (ACLS Teagle Working Group in Liberal Education, 2007) concludes that the "teacher-scholar model of faculty professional activity brings benefits of great import to individual student learners, institutions where that model flourishes, and society more broadly." Implementing TR enhances both the model and the effectiveness of the teacher-scholar in the liberal-arts environment. It stimulates growth for the individual faculty member, providing constant encouragement to incorporate the current literature in the field, to consider new approaches to significant unanswered questions in the field, to interact with colleagues beyond his or her own discipline, and to help students approach problems with commitment and creativity.

A primary mission at PUIs is to stimulate intellectual growth in our students, but another goal is to help them embrace the challenges of the world ahead—blending scientific discipline with creativity to arrive at new, transformative solutions that presently elude us. If we do not provide a model for that kind of ambition in intellectual endeavors, where will it come from? Significant growth can occur through the process of tackling the great challenges of our times: the environment, disease, social ills, the inner workings of the human brain, and so forth. Conducting research on topics such as those will change us, and as we change, our undergraduates will be a part of the process. They will be collaborators in projects with goals that are irreplaceable and potentially life changing. A vision of the future of TR simply cannot leave out undergraduates or their faculty mentors, and there is no better educational environment for undergraduates than one that fosters innovation and challenges all of us to accomplish more.

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The Role of Department Chairs in Promoting and Supporting Transformative Research

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Much has been written about leadership in academe, including how to be an effective department chair and how to shape change. However, despite much reading and many years in the role of chair, I personally have never seen anything that provides specific advice on how a chair could promote transformative research in a department.

A typical recommendation for leading an organizational unit through change is to begin by having the group members realize a common vision and purpose. In academe, this may be possible if the goals include such things as updating or improving the curriculum, increasing the success of students majoring in the department, or enhancing the reputation of the department (in teaching innovations, student accomplishments, or scholarship). But given how rare it is for anyone to have an experimental breakthrough that changes a scientific paradigm, the notion of identifying a common department goal of transformative research seems completely illogical. (There are still individuals at undergraduate institutions who don't believe that *any* type of research is part of the departmental or institutional mission.)

It is conceivable, however, that in trying to achieve some of the other departmental goals noted above, a chair could help lead the department through changes that would have the added benefit of creating an environment that is *conducive* to transformative research.

It is not my intention to reiterate what others have written about academic leadership or organizational change. However, in thinking about what department chairs (especially those at predominantly undergraduate institutions) could do to help create an environment that is favorable for transformative research, I developed a list of questions that I explore in this chapter:

- What does it take to create a vibrant and productive science department for the twenty-first century and what is the department chair's role in promoting such change?

- If a department chair can help to create a dynamic contemporary science department, would that not also lead to an environment that would nurture creative thinking and innovation among the faculty and students and thus, in turn, set in place the key prerequisites for transformative research to become a possibility? In other words, what is the relationship, if any, between an innovative, productive department (in terms of curriculum and scholarship) and the criteria necessary to support transformative research?
- How can a department chair support and protect faculty members who are risk-takers and innovators in an environment where the primary focus is undergraduate education? What can a chair say to those who may not see transformative research and teaching as compatible, much less synergistic endeavors?
- And if a departmental colleague is successful in having a major breakthrough in his or her research, what is the role of the department chair in managing the subsequent consequences that are bound to impact the entire department?

I believe that department chairs who are attentive to the national trends in STEM (science, technology, engineering, and mathematics) education and funding, and who are cognizant of the advances in the disciplines represented by the department, will also be the ones who routinely evaluate and initiate revisions of the mission and curriculum. These leaders will continuously strive to enhance the intellectual culture of the department and by doing so, will attract and retain both bright students who become deeply engaged in meaningful learning opportunities and dynamic faculty members who are talented teachers and researchers. Add the appropriate resources to support high-quality research (for which chairs have to be strong advocates), including time for the generation of ideas, and the academic departments that these chairs steer will have the right ingredients in place to cultivate creativity, which just might result in research that is transformative.

Department Chairs Should Follow National STEM Efforts.

For some time, it has been evident that the United States has been losing its competitiveness both in terms of how well students perform in STEM fields and in terms of our innovation in science and technology. The consequences of this decline were convincingly outlined in the report *Rising Above the Gathering Storm* (National Academies Press, 2007):

> *Having reviewed trends in the United States and abroad, the committee is deeply concerned that the scientific and technological building blocks critical to our economic leadership are eroding at a time when many other nations are gathering strength. …We are worried about the future prosperity of the United States. Although many people assume that the United States will always be a world leader in science and technology, this may not continue to be the case inasmuch as great minds and ideas exist throughout the world. We fear the abruptness with which a lead in science and technology can be lost—and the difficulty of recovering a lead once lost, if indeed it can be regained at all.*

This report continues to generate a great deal of national dialogue and was influential in the drafting of the America COMPETES Act[1] signed into law by President George W. Bush in August 2007. Provisions of the act, which focuses heavily on innovation and competitiveness, have implications for the Office of Science and Technology Policy, the Department of Education, the National Science Foundation, and many other government agencies (e.g., NASA, NIST, NOAA, and DOE)—and thus for anyone interested in funding for research or curricular reform in STEM fields.

In 2008, a related report was published, *Advancing Research in Science and Engineering. Investing in Early-Career Scientists and High-Risk, High-Reward Research* (The American Academy of Arts and Sciences, 2008). The executive summary of this ARISE report begins:

> *Leadership in science and technology is necessary to compete effectively in the global economy. Today the dominant position of the United States in the international research and education community is being challenged as never before.*

The authors continue:

> *University research programs in science and engineering are essential to America's technological innovation, economic prosperity, health, national security, and quality of life. …We strongly believe that, regardless of overall federal research funding levels, America must invest in young scientists and transformative research in order to sustain its ability to compete in the new global environment.*

I will take the liberty of expanding this statement to include the importance of research conducted by undergraduates and at undergraduate institutions (that is, not just research universities) and note that I strongly believe in the important role that undergraduate education plays in developing the students who will go on to graduate school and careers in scientific research.

Both of these national reports clearly link science and technology to the economic status of our country and speak of the critical importance of innovation (and transformative research) in the continuing competitiveness of the nation in a global economy. A savvy chair of a STEM department should consequently recognize that these reports provide a blueprint for the direction of science, technology, and STEM education in this country. As such, they are

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[1]The America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science Act was a bipartisan legislative response to recommendations contained in the National Academies' "Rising Above the Gathering Storm" report and the Council on Competitiveness' "Innovate America" report. The act was similar to the National Competitiveness Investment Act introduced by Senate science leaders in September 2006. See http://www.osa.org/News/publicpolicy/documents/SUMMARY%20OF%20THE%20AMERICA%20COMPETES%20ACT%202-26-07.pdf for more information.

important when considering ways to attract more students into STEM fields, redesigning curricula that will meet both student and workforce needs, or soliciting research funds.

I have often been amazed to hear faculty members express skepticism or concern about linking department aspirations and initiatives with national goals and priorities or, in the case of public institutions, the state and regional political agenda. In my opinion, this is naïve, especially when higher education is increasingly being asked by the government to be accountable for how well students are learning and how effectively tax and tuition dollars are being spent. It is easier to justify what you are trying to accomplish if you can demonstrate how your goals align with state or national priorities.

At liberal-arts institutions, it is also common to hear remarks from faculty members to the effect that they aren't in the business of preparing students for careers, but rather to develop lifelong learners and critical thinkers. Given this mindset, my suggestions to pay close attention to the external indicators arising in the workplace outside of academe or to mandates in the national political agenda might seem unusual or perhaps even irrelevant. However, to people like college presidents and the leaders of our disciplinary societies—who pay careful attention to deliberations in Washington and also to changes in demographics and economic indicators—it is clear that changes in higher education and STEM funding priorities are inevitable. Federal and state funds that support education and STEM research *will* be closely linked to the national priorities. So like it or not, department chairs at *all* types of institutions should be paying more attention to such matters.

That change is occurring, even within the liberal-education circles, is also demonstrated by the new emphases within the Association of American Colleges and Universities (AAC&U). Liberal education is no longer the domain of private liberal-arts colleges, the group says, but is increasingly also a part of the culture and mission of public comprehensive institutions and community colleges. Further, the organization is heavily focused on what is known as the LEAP initiative (AAC&U, 2009):

> *Liberal Education and America's Promise (LEAP) is an initiative that champions the value of a liberal education—for individual students and for a nation dependent on <u>economic creativity</u> and democratic vitality* (emphasis added).

Thus, even an organization that labels itself "A Voice and a Force for Liberal Education in the 21st Century" (http://www.aacu.org/) is acknowledging the essential links among education, creativity (innovation), and economic leadership for the future of this country. The LEAP initiative focuses strongly on these connections and is exploring how a liberal education can help prepare our students to make a difference in our world. This indeed represents a transformation in how we think about a liberal education.

Even if a department chair is not currently focused on these national reports and indicators, he or she should be facilitating conversations about how the disciplines represented by the department are changing and why. A chair, along with other department members, should be continually reading the scientific literature in the fields the department encompasses, as well as tracking trends in the educational literature to see which innovative concepts, methods, and equipment their students should be exposed to. It shouldn't take long to realize that both the ways in which science is done and the pedagogies used in the twenty-first century are changing rapidly and dramatically. The questions now being studied and the nature of the problems to be solved typically require collaborative, interdisciplinary teams, as well as technologies that might not have even existed just a few years ago.

I think that it is a good idea for department chairs to ask their faculty members to review the grand challenges that have been identified for science and engineering (National Academy of Engineers, 2009; National Research Council, 2001; Bill and Melinda Gates Foundation, 2003). They should also schedule a department meeting at which faculty members share observations on some emerging innovations or controversial topics in each of their specific areas of expertise. Discussions should then center on whether the department is doing the right things to prepare students to be the next generation of problem solvers—to become the individuals who might work at the forefront of the discipline to help solve some of the challenges identified. The list of discussion topics that will be covered probably won't differ much from the national political agenda, but the conversations will be framed within the context of faculty members' scientific disciplines and thus may be more palatable.

In short, if we want our students to be successful, contributing members of our disciplines, then we need to be constantly rethinking how and what we teach them, how they learn, and what the most important areas of focus should be in the classroom and beyond. An effective chair will be leading such conversations within the department and be prompting the faculty to routinely benchmark where they are in terms of their curriculum and research competitiveness (success in acquiring external funds, producing peer-reviewed publications, etc.). The external changes within our disciplines and the STEM workforce should challenge us to rethink how we teach and work with students to create new knowledge. Not surprisingly, many of the trends (e.g., team collaboration, interdisciplinary approaches in research, and the incorporation of cutting-edge technologies) are also conducive to promoting transformative research.

Department Chairs Should Articulate How National Trends Align with Departmental and Institutional Missions.

Faculty members at predominantly undergraduate institutions are used to hearing the mantra that their primary mission is *teaching*. Does this mean that scholarship is to be ignored? Of course not. It is generally accepted within higher education that, besides teaching, another function of academe is to advance knowledge. If faculty members and students are not doing research, how can this be accomplished? Despite a number of publications in the educational literature that question whether faculty members can balance good teaching and research (see Elton, 1986; Page, 1972; Schmitt, 1965), it has been documented that faculty who are active scholars remain invigorated longer in their careers (for example, see Mills, 2000). In a 2007 white paper by the Teagle Foundation, the authors provide a strong rationale supporting the teacher-scholar model (American Council of Learned Societies, 2007).The combination of this vitality and the disciplinary currency that scholarship demands presumably (hopefully) are translated into the classroom, underscoring why the teacher-scholar model is strongly advocated at institutions ranging from community colleges to research universities.

While teaching-research relationships may be complex (Jenkins, 2004), the importance of research in undergraduate STEM education has clearly been recognized by the scientific community, including by many disciplinary societies. For example, the American Chemical Society's Guidelines for Bachelor's Degrees (ACS, 2008) state:

> *Undergraduate research allows students to integrate and reinforce chemistry knowledge from their formal course work, develop their scientific and professional skills, and create new scientific knowledge. A vigorous research program is also an effective means of keeping faculty current in their fields and provides a basis for acquiring modern instrumentation. Original research culminating in a comprehensive written report provides an effective means for integrating undergraduate learning experiences, and allows students to participate directly in the process of science.*

Over the past year, the CUR Physics and Astronomy Division developed the following statement, which has now been adopted by a number of professional societies including the Committee on Education of the American Physical Society, the American Astronomical Society, and the Society of Physics Students:

> *We call upon this nation's physics and astronomy departments to provide, as an element of best practice, all undergraduate physics and astronomy majors a significant research experience.*

As a third example (there are many more), the curriculum recommended by the American Society for Biochemistry and Molecular Biology notes, "Research experience is an essential part of the undergraduate experience in biochemistry and molecular biology," and the society strongly recommends that "experimentally-based research experience including a formal proposal, report and presentations" be a core part of the curriculum. The document lists a number of research proficiencies as "skills that biochemistry and molecular biology students should obtain by the time they have finished their undergraduate program." This list includes not only skills involving experimental design and interpretation of data, but also things like awareness of the major issues at the forefront of the discipline, ability to assess primary papers critically, and ability to collaborate with other researchers.

Higher-education organizations such as CUR, AAC&U, and Project Kaleidoscope have acknowledged in their publications that engaging undergraduates in research is a high-impact, experiential form of learning (AAC&U, 2006; Project Kaleidoscope, 1989). Department chairs should be familiar with the growing list of literature on this topic, especially within the disciplines represented by the department, and should promote both the teacher-scholar model and undergraduate research as important expectations and components of the departmental mission.

Department chairs should insist that department members periodically review the departmental mission (or create one if it doesn't exist). A key question during such discussions is "What is it that you want your graduates to 'look like' (or be able to do)"? During the dialogue, connections between the program's learning goals and components of the mission statement should become clear. At Moravian College, a private liberal-arts college of fewer than 1,600 full-time undergraduates, we developed a mission statement for the Department of Biological Sciences (http://home.moravian.edu/public/bio/):

> *The mission of the Department of Biological Sciences is to instill in our students an understanding and appreciation of the common thread that connects modern biological study at all levels, from molecules to ecosystems. We strive to actively engage our students in the process of scientific investigation, develop their spirit of inquiry, strengthen their ability to explore both in field and laboratory, hone their analytical skills, and foster their capacity to communicate effectively with professional peers and the public. By helping students become independent thinkers and intellectually vibrant individuals, we hope to enable them to achieve a lifetime of personal and professional success and service to society.*

The statement goes on to say:

> *Biology majors use current methodological approaches in laboratories, learn about the intricacies of the subject in class, and discuss recent research findings in seminars. All students are encouraged to participate in an independent study or Honors project, in which they can work closely with a member of the biology faculty on a research topic.*

These statements do not specifically say anything about transformative research. However, if we are remotely successful in meeting the goals that stem from this mission statement, we are certainly doing much to develop the mindset and skills that our students need in order to be innovative scientific researchers. And, if faculty members and students do have major breakthroughs in their research, it certainly wouldn't be incompatible with the mission we have set forth. Indeed, we have two faculty members and a number of students from the department who have participated in transformative research. (See chapter Seven.) A third faculty member in the department is involved in an innovative and collaborative research-rich, national educational initiative that was featured in *Science* (Lopatto, *et al*, 2008).

Besides aspiring to provide a liberal education, a number of campuses now have references in their mission statements regarding preparing students for "service for the common good." The phrase "common good" is a bit vague and subjective, but if we could prepare students to work on some of the global problems confronting humanity, I am pretty certain that would qualify. Just as departments should be discussing the grand challenges facing their disciplines, so too should faculty discuss these topics with students in classes or departmental seminars. Such dialogue would ideally involve multiple departments given the interdisciplinary nature of many of the topics—environmental sciences (e.g., biological diversity, ecosystem functioning, climate variability, and hydrologic forecasting); sustainability (e.g., finding renewable, clean energy solutions or "greener" materials that lessen our dependence on diminishing natural resources); or global health (development of new vaccines or control of disease vectors or infections). Alternatively, faculty members could discuss with their students the United Nations Millennium Development Goals (ending hunger, improving maternal and child health, combating HIV/AIDS, environmental sustainability) and the roles that STEM fields might play in helping to achieve them. It should quickly become obvious that the biggest challenges confronting society and the planet are issues that, first, will require scientific and technological contributions to help solve them and, second, if solved, would most certainly lead to benefits for the "common good." And certainly, transformative research will be needed to achieve breakthroughs in any of these areas.

When there is a campus-wide discussion of mission, once again it is valuable for department chairs to be cognizant of the national conversations. In defining liberal education, the AAC&U LEAP initiative speaks of preparing individuals to deal with complexity—to "develop a sense of social responsibility, as well as strong and transferable intellectual and practical skills such as communication, analytical and problem-solving skills, and a demonstrated ability to apply knowledge and skills in real-world settings." (See http://www.aacu.org/leap for further information.) Routinely, departments are being asked to justify how their programs relate to the institutional mission (for accreditation, budget requests, strategic planning, program reviews, etc.). A keen chair will be able to clearly articulate the links among the departmental goals, curriculum, and scholarship; the provision of a liberal education for students; and the role that their discipline can and does play in helping to address contemporary societal problems. It doesn't hurt to mention that a department is also creating the proper environment to inspire the next generation of innovators.

The goal of creating an academic environment that could lead to transformative research is certainly not contrary to the institutional goals of liberally educating students and preparing them for making a positive impact on society. Indeed, students who are being taught in an environment that promotes critical thinking, a sense of social responsibility, and the application of knowledge gained to solve real-world problems are *precisely* the type of students who will likely be the next generation of innovators. Arden L. Bement, Jr., Director of the National Science Foundation, said in a speech on transformative research that "Education is also a potent source of transformation" (Bement, 2007). He was referring to graduate-level studies, but good graduate students are nurtured and "turned on" to a research future at the undergraduate level.

The importance of educating undergraduates is boldly stated in the chapter entitled Undergraduate, Graduate, and Postgraduate Education in Science, Engineering, and Mathematics in the *Rising above the Gathering Storm* report (National Academies Press, 2007):

> *"The undergraduate years have a profound influence both on future professionals in science and mathematics and on broader public support of those fields. Undergraduate education acts as a springboard for students who choose to major in and then pursue graduate work in science and mathematics. Undergraduate institutions and community colleges train the technical support personnel who will keep our technological society functioning smoothly in the years ahead. And colleges and universities prepare the elementary and secondary teachers who impart lifelong knowledge and attitudes about science and mathematics to their students."*

Of course, most undergraduates will never be involved in research that is transformative during their undergraduate years or even in their entire career. However, undergraduate departments that provide opportunities for students to become excited about research and develop a range of research proficiencies are providing a rich learning environment for their students. These students will not only see the relevance of their classroom learning, but also will develop confidence, independence in the laboratory or field, be given the opportunity to be creative, and, hopefully, gain a strong sense of ethical responsibility. In other words, these graduates will have the skills to go on to graduate school or industry where they just might be involved in major scientific and technological breakthroughs. Even if they don't do transformative research, or even work in a STEM field, all of our students will be taxpayers and (we hope) voters who can help determine national science policy and call for enhanced support of scientific research. Imagine graduates who are civicly engaged, globally aware, scientifically literate, and have the ability to research an issue, critically analyze information, and employ problem-solving skills. Not bad outcomes for departments and institutions with a mission of liberal education. Such are the stories that a STEM department chair should tell.

Department Chairs Must Work to Ensure Relevant Curricula Aligned with Departmental and Institutional Missions.

It should be obvious, given the pace of advances in most STEM fields, that departments should be routinely reviewing their curricula to see if they are current and relevant. However, guiding curricular revisions can be extremely challenging as academicians don't always readily embrace change and often are very protective of their turf (i.e., what occurs in *their* classrooms is considered their academic freedom). Of course, chairs can't unilaterally impose major changes on programs and courses offered by a department. There are often long-running philosophical debates among faculty members as to whether it is most important to teach fundamental concepts and basic laboratory skills (letting students get specialized experience "on-the-job") versus whether students should be introduced to cutting-edge ideas and technologies to get them excited about the type of science they might actually be doing after they graduate. In my experience, if a department's curriculum is out of date, it is likely to be a symptom of other problems as well. Despite the challenges involved, chairs must make sure that there is ongoing dialogue about curricula and any revisions that might be necessary to realign offerings with contemporary trends in the disciplines and with the departmental and institutional missions.

There is a tendency in higher education to bring in outside evaluators to review programs and curricular content. Outside perspectives can provide departments with valuable insights and a "fresh look." However, as someone who has gone through a number of external program reviews and served as an evaluator for many departments, I know that many reviewers tend to view programs through traditional sets of lenses and can be rather cautious in their recommendations. If a department is trying things (or wants to) that are innovative or even a bit risky, these unusual ideas might not be fully appreciated or supported by these evaluators. If chairs want to promote some curricular innovation and have outside "experts" support these ideas, they will need to do a bit of background checking before the reviewers are invited to campus. As noted by the current head of the National Science Foundation (Bement, 2007):

> *We try to make sure that we are not complacent in searching out new paradigms, that we encourage different points of view and different perspectives, and that we make risk-taking acceptable and welcome.*

In my opinion, two aspects of the curriculum in STEM fields that are musts for the twenty-first century are that it should be research-rich and, to the extent possible, interdisciplinary. In an article on intentional and integrated learning, Youatt and Wilcox examined contemporary pedagogical practices:

> *As we examined our own best practices, we discovered examples of educational practices and programs that we believed constituted a newly emerging signature pedagogy for undergraduate education. …This new signature pedagogy can be characterized as discovery-centered, interdisciplinary, integrative, translational, and contextual. Although any one of these characteristics can contribute to an important and meaningful learning experience, it is the five together, interconnected in a program or experience, that results in the kind of twenty-first-century learning we are striving to achieve and assess. …Discovery-centered learning encourages students to produce original work that contributes to the knowledge or activity of a particular discipline or disciplines. It is research in the broadest sense—the finding out of something new that expands a working body of knowledge* (Youatt and Wilcox, 2008).

In 2003, an NSF-sponsored Summit on Undergraduate Research was held at Bates College (see http://abacus.bates.edu/acad/depts/chemistry/twenzel/summit.html). A major theme discussed at this gathering was how to develop a research-rich curriculum. My coauthor, Tim Elgren and I argued in a white paper on this topic prepared in advance of the summit that besides having students engage in capstone research experiences, courses *throughout* the four-year curriculum should help to hone important research skills. Such skills include searching, reading, and evaluating the scientific literature; articulating concise and feasible research questions; designing experiments; gaining a knowledge of research ethics and laboratory safety; collecting, assessing and communicating experimental data and conclusions (where the results aren't known at the onset of the experiment as is often the case in traditional laboratory exercises); and articulating the nature of the research and its significance (Husic and Elgren, 2003).

It is valuable for department chairs to initiate conversations with faculty members to see which of these research elements, if any, are incorporated into their courses. Department-wide discussions should occur to help integrate and coordinate research-rich experiences throughout the curriculum; to consider what sort of scheduling and class size allow the flexibility to integrate authentic research experiences into courses; and to determine what departmental resources (budget, laboratory space, up-to-date equipment, access to field sites, computers, etc.) are needed to support such endeavors. Department chairs can help find and schedule blocks of time for regular departmental seminars (for guest speakers, for faculty and students to present research) and journal club sessions. In other words, individual faculty members can incorporate research-rich ideas into their individual courses, but chairs must lead a department-wide initiative to cultivate a research culture for the students and the department as a whole. Without such a *culture*, it is unlikely that transformative research would be seen as consistent with the department's mission.

Chairs can provide subtle reminders of the value of research experiences in student learning by posting relevant quotes on department bulletin boards or in messages to colleagues, and by fostering conversations about this concept in department meetings. I came across the following two quotes and plan to use them in our curricular-revision discussions:

> *The new science of learning is beginning to provide knowledge to improve significantly people's ability to become active learners who seek to understand complex subject matter and are better prepared to transfer what they have learned to new problems and settings* (National Research Council, 1999).

> *It's our part …to help our students develop minds subtle and deft enough to solve complex problems. We need to give them guided practice at articulating the problem in a mass of information and then coming up with solutions A, B, C, and so on until they hit on one that works at a cost we can bear. Our little miracle will be to educate students who are intellectually nimble enough to take care of the unexpected side effects of those very solutions (as when ethanol, designed to solve the energy problem, creates a hunger problem) and flexible enough to give up their cherished idea to move on to one that works better* (Miller, 2009).

Department chairs in STEM disciplines (and beyond) should also be touting the importance of interdisciplinarity—in problem solving, for research, and within the curriculum. As I've noted, most of the grand challenges we face are going to require interdisciplinary approaches to solve and thus we must be preparing students to think across disciplinary boundaries, recognize the capabilities and limitations of our primary fields of expertise, and know when to collaborate with others from different disciplines in order to solve a problem at hand. There are many obstacles to working across disciplines (see for instance, Husic, 2006). Many faculty members describe interdisciplinary teaching and research as "messy." However, I firmly believe that this is an imperative if we want our departments and students to flourish. A major initiative for facilitating interdisciplinary learning is under way through Project Kaleidoscope, sponsored by the Keck Foundation (see http://www.pkal.org/activities/PVIIDST.cfm). Chairs should be on the lookout for the final report and resources forthcoming from this project. In the meantime, they can help to nurture interdisciplinary connections between their departments and other disciplines.

Chairs can encourage their faculty members to explore opportunities for interdisciplinary teaching, and they can also be initiating conversations with chairs in other departments about the possibility of interdisciplinary, first-year laboratories or senior seminars in the STEM fields. The more adventurous departments might even consider more broadly based interdisciplinary courses involving the sciences and departments outside of the STEM fields.

To be provocative, I recommend the following pair of quotes for department bulletin boards (National Academy of Sciences, 2004; emphases added):

> *Interdisciplinary research (IDR) can be one of the most productive and inspiring of human pursuits—one that provides a format for conversations and connections that lead to new knowledge. As a mode of discovery and education, it has delivered much already and promises more—a sustainable environment, healthier and more prosperous lives, new discoveries and technologies to inspire young minds, and a deeper understanding of our place in space and time.*
>
> *Interdisciplinary research and education are inspired by the drive to solve complex questions and problems, whether generated by scientific curiosity or by society, and lead researchers in different disciplines to meet at the interfaces and frontiers of those disciplines and even to cross frontiers to form new disciplines.*

Department Chairs Must Support Faculty Who Seek to Explore Knowledge and Innovation.

One of the most important things that a department chair can do is to empower the faculty in their department. A chair should periodically sit down and talk with each member of the department to learn about his or her personal and professional goals. This is essential, of course, for evaluation processes, but it is also important to help a chair find ways to enable faculty members to be successful in reaching their teaching and research goals. Chairs should be supportive of creative ideas and work with faculty members in efforts to secure resources (including time) for research, attending conferences, and writing grants.

Chairs can gently encourage faculty members to move beyond their comfort zones—to learn new skills, to think about developing interdisciplinary courses, or to pursue some riskier forms of research if individuals have sound ideas but are hesitant to move in new directions. Some of the most creative faculty members that I know unfortunately are not necessarily viewed favorably by colleagues in their department; instead they are described as being a "bit out there" or "boat rockers." The ones who are the most successful typically have a very supportive chair or dean who continues to encourage them to pursue ideas that aren't so ordinary and who praise the accomplishments that arise from their creativity. As noted by H. Bradley Sagen (2008):

> *Group involvement sometimes restricts legitimate individual initiative. In some measure, therefore the organization must protect innovative faculty from other faculty.*

Since chairs are typically responsible for developing teaching schedules, they should attempt to create blocks of time for faculty members to focus on scholarship. This might be specific days without classes or having a faculty member teaching a disproportionate load for a portion of the semester but very little during the other part. For instance, if a department offers multiple sections of introductory courses in a given semester, one faculty member might teach several sections for the first third or half of the semester, but then have other faculty members take over later. (This tag-team teaching format necessitates creative planning and organization, but can introduce students to diverse ideas and different styles of doing things beginning their first year on campus.) Faculty then theoretically have uninterrupted time built into their schedules for creative thinking (needed for idea generation), carrying out research, nurturing conversations across campus or meeting with collaborators, attending meetings, or writing proposals or manuscripts. Chairs should try to keep at least one time slot open each week for departmental seminars, journal club sessions, or informal discussions—separate from departmental meetings where routine business must be done. And chairs should support flexibility so that colleagues can occasionally adjust their schedules or swap courses with colleagues when they want to attend a conference or are asked to give a presentation somewhere off campus.

The ARISE report (American Academy of Arts and Sciences, 2008) identified support for early-career faculty members as one of "two issues central to the nation's research efforts that have not received sufficient attention." The report states:

> *Today's early-career faculty will be responsible for our country's future science and technology discoveries and for the education of our future Ph.D.-level scientists and engineers. Yet they face greater obstacles than their more senior colleagues in securing research grants to inaugurate what should be one of the most productive stages of their careers.*

One of the key recommendations in the report is "to actively mentor early-career scientists." Department chairs can serve as mentors or facilitate pairing up the new faculty member with an appropriate, established member of the department. Having a mentoring program in place sends a strong positive message to candidates for positions and to new faculty. And sometimes, senior faculty members paired up with new faculty members can learn a thing or two as well! In any case, it promotes communication and collegiality within the department.

Sometimes, new faculty members may not be comfortable asking certain things of faculty who may be involved in their pre-tenure evaluations, so chairs should be sensitive to this and suggest networking with colleagues outside of the department. This could be with faculty members in different departments, through programs such as CUR's mentoring service, through attendance at programs offered by disciplinary societies (such as the Getting Started in Undergraduate Research session at American Chemical Society meetings, organized by CUR Chemistry Division councilors), or with research collaborators whom they can also ask for career advice.

Another recommendation in the ARISE report is to find seed funding for new faculty members that will "enable them to explore new ideas for which no results have yet been achieved." Department chairs need to encourage new faculty to seek out grant opportunities early in their careers, but internal funds can be very useful to help a faculty member initiate some innovative and perhaps riskier ideas in order to provide some proof of concept. (Internal funds are also valuable for more established faculty who also want to explore a new area of research in which they don't have an established track record.)

The 2004 report *Facilitating Interdisciplinary Research* (National Academy Press, 2004) described how current systems discriminate against researchers who work in an interdisciplinary environment. In contrast, reports on transformative research discuss how important it is to work across disciplinary boundaries. In light of this incongruity, a major issue brought up both at the CUR Summit on Transformative Research and in the ARISE report is that if faculty members are to be encouraged to consider riskier, collaborative, and/or interdisciplinary research, revisions may be needed in department and campus-wide promotion and tenure policies. For example, faculty members who collaborate, often as a part of an interdisciplinary team, and in turn publish papers with multiple coauthors are often given less "credit" (even if they are first author) than someone who is a single author of a manuscript (for instance, see Desselle, Mattei, Vanderveen, 2004). Faculty who make significant contributions to such projects should be encouraged and not penalized. Additionally, some types of innovative or use-defined projects have non-traditional outcomes (i.e., other than peer-reviewed manuscripts), and policies should be flexible enough to allow faculty to submit other types of outcomes as a measure of scholarly productivity and have them *seriously* considered. Department chairs can serve as an advocate for these faculty members by explaining in their evaluation reports the significance of these collaborations and non-traditional scholarly contributions or products.

It is difficult for a single department to have a policy that differs widely from the campus norm. Thus, chairs of STEM departments should work together on educating faculty across disciplines (including in their own departments) and educating the administration about alternative measures of research quality. As a team, they are more likely to be effective than a single individual will be in getting campus-wide policies reviewed and possibly revised.

Department chairs also need to work with their colleagues in other STEM departments to develop a division-wide climate that is supportive of transformative research. For instance, because of the interrelatedness of the science curricula (i.e., co-requisite courses), if one department starts making major adjustments in how it schedules its courses, in order to create blocks of time for scholarship, this may have a significant impact on the programs of other departments. Chairs of STEM departments can work together to develop some common strategic initiatives, such as establishing a science seminar series that focuses on research at the interface of disciplines or that examines some of the "big questions" confronting society. Perhaps once or twice a semester, they could sponsor cross-disciplinary journal clubs and other gatherings at which interdisciplinary initiatives are discussed or celebrated.

I am a firm believer that STEM chairs have to create a united front when seeking resources to support research and new initiatives. Resources might include properly designed research spaces that promote cross-fertilization of ideas and collaboration (between students and faculty), equipment priorities, course loads (that count lab teaching fairly), and support staff (for lab preparation, instrument maintenance, etc.). Not only can such resources promote interdisciplinarity, but such cooperation and resource sharing between departments is also likely to be viewed favorably by administration.

If STEM chairs are used to working together in such a collaborative way, they can begin to initiate dialogue about some additional ideas that are newer to undergraduate institutions. This might include hiring laboratory technicians to help support research (instead of solely teaching); clustering hiring around a common theme to facilitate collaborative research; or acquiring endowed faculty positions to create opportunities for interdisciplinary hires or attract established researchers who could devote their energies to riskier research. If a campus does not already employ postdoctoral fellows, STEM chairs could begin explaining to their departmental colleagues and to administrators how valuable these positions can be. There are well-established models that show that not only do the postdocs gain experience in an institution that promotes the teacher-scholar model, but also that they, in turn, provide benefits to the students and faculty in a department through their fresh ideas and experience with new laboratory methods. They can contribute to the research culture (and productivity) of the department; mentor students, and model one aspect of the professional-development spectrum that might not otherwise occur at the institution. Depending on their backgrounds, they might also be able to teach an interdisciplinary special topics course appropriate for students in more than one department at the institution.

Enlisting the support of the other STEM chairs can also be critical if the need should arise to explain to colleagues outside of the sciences why efforts aimed at enhancing a research culture align with the (teaching) mission of the institution. Since liberal-arts colleges are home to faculty members who might very well view transformative or use-inspired research as too applied, a single chair making the arguments I've outlined won't be nearly as effective as a united team doing so.

While none of the suggestions I have made will guarantee that scientific breakthroughs will occur in a department, it seems appropriate to end this chapter with some consideration of "what if"? What if someone in your department has a major research breakthrough and all of a sudden, the individual, and possibly the department, is cast into the limelight?

If there has been an open dialogue in the department about the value of research and its synergies with teaching, learning, and departmental mission, then the success should readily be recognized as important for the individual, the discipline, and the department—something to be celebrated. However, the researcher involved is apt to receive a lot of attention and become the "darling" of administration, leading to feelings of resentment among colleagues. This can be particularly true for some senior members of the department who may no longer be involved in research; they may feel as though their ongoing service and many years of contributions to the institution are no longer of significant value. Faculty members who have made steady, incremental advances in their research may also wonder if their scholarly contributions are valued any longer, especially if their successes were never spotlighted by the institution.

Chairs must continue to indicate the importance of students and faculty engaging in high-quality research of *all* types and the importance of the *team's* contributions to the department and to individual successes. For instance, did someone in the department pick up a larger share of teaching to provide extra time for the faculty member now in the limelight to conduct the research? Did a more senior faculty member relinquish some research space for the new "star"? And, of course, a chair will remind the department members that success in academe is measured by contributions of many sorts in teaching, service, and scholarly accomplishments and in the overall support of a culture that advances knowledge. It doesn't hurt to remind them that individual successes that garner a lot of attention actually help raise the entire department's "boat" in terms of how the department is viewed on campus by prospective students, as well as by alumni and potential donors.

If the breakthrough is of great enough significance, it could attract media attention. In this case, the chair may need to protect the faculty member's time and help the individual to keep a focus on work that still must get done. Such attention, of course, can go to a person's head and create prima donna-like behavior, so a chair has to recognize such symptoms and have a straightforward conversation with the individual. Faculty members who have scientific breakthroughs may also begin to receive offers for other jobs. A chair, of course, can't decide whether it is best for the faculty member to stay or move on, but the chair can listen in confidence as the individual works through the options and then can be supportive of whatever decision the individual makes. If a faculty member decides to leave, the chair can use the occasion to tell prospective candidates for the newly created opening that the department has an environment that nurtures creativity and allows people to be highly successful in their research. In these circumstances, recruiting a great replacement colleague should not be very difficult.

Conclusion

In discussing the essential ingredients in effective change-making, Lloyd Averill (1983) lists the importance of creating "an enlarged 'sense of the possible' among the institution's members." There are a number of things that an effective department chair can do to provide a grander vision for his or her department members as they work to create an environment that would support research that is transformative in nature. There are no guarantees, but the efforts will likely result in a research-rich and increasingly interdisciplinary curriculum and department culture; enhanced resources and support for faculty and student research; a more stimulating environment for learning; good collegiality and intellectual discussions; and new stories that can be told to students, job candidates, administrators, alumni, funding agencies, and potential donors. If someone produces a transformative breakthrough—fantastic. If not, the resulting dynamic, contemporary science department is still something well worth celebrating.

Here is one last quote for readers to ponder:

> *To manage meaningful and sustained "transformation" of the culture requires mastery of its dynamics; it requires statesmanship"* (Halonen, ter Haar, Ellenberg, 2008).

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Transformative Research as a Means of Transforming Landscapes and Revitalizing Academic Departments: A Case Study

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Background

By December 1980 when President Jimmy Carter signed the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA, better known as the Superfund legislation), the U.S. public was already well aware of the consequences of decades of environmental exploitation.

Whether it was air quality so poor that the pollution could be seen from space, rivers catching on fire, the discovery of buried tanks and drums leaking toxic substances into the ground, or finding that dioxin, PCBs, and suspect carcinogens were leaching into backyards, basements, and schools, it had become excruciatingly clear that environmental tragedies were all too common. The new legislation was put into place, not to regulate new sources of pollution, but to deal with "abandoned, accidentally spilled, or illegally dumped hazardous waste that posed current or future threats to human health or the environment" (US EPA, 2005).

Since that time, major strides have been made in finding ways to contain contamination and to treat, store, and dispose of hazardous wastes. As of May 2009, 1,596 sites have been placed on the National Priorities List (NPL), which designates the sites that pose the greatest risks under the provisions of CERCLA. At least some remediation work has been done at most of these, but, over the past three decades, only about a fifth of the sites have been deleted from the list—an indication that the clean-up work was completed (US EPA, 2005). EPA's work at NPL sites involves determining responsible parties, identifying unacceptable human exposures, controlling migration of contamination, construction related to remediation efforts, and five-year reviews.

Despite billions of dollars and extensive clean-up efforts, however, one in four Americans still lives within four miles of a Superfund site (US EPA, 2005) and it is estimated that about 11 million people in the U.S., including three to four million children, live within one mile of one of these sites (Scorecard, 2005). And an additional 67 sites have been proposed to be added to the NPL (be Specific, 2009).

The concept of redevelopment of Superfund sites—returning the land to productive use—has been around since the late 1990s. Industrial parks, shopping centers, recreational areas or sports fields are possible examples of redevelopment. If a site is simply categorized as "under control" and then left as a vacant, fenced-off area, the land has no value and can't contribute to a municipal or county tax base. Such sites are eyesores and contribute to the anxiety of people living or working nearby. At the end of 2008, the cumulative total of sites ready for anticipated reuse was 343, with a target of adding 65 additional sites in 2009; however, only a little over one-third of these sites have actually been recycled – usually for commercial development (US EPA, 2009 a, b).

Even newer than the goal of recycling Superfund sites, is the focus on ecological reuse—returning "polluted or otherwise disturbed lands to a functioning and sustainable use by increasing or improving habitat for plants and animals" (US EPA, 2009 c). The latest EPA strategic plan includes an objective of enhancing science and research as part of the goal of land preservation and restoration:

> *Provide and apply sound science for protecting and restoring land by conducting leading-edge research, which, through collaboration, leads to preferred environmental outcomes* (US EPA, 2006).

This objective describes *transformative research* in that it calls for collaborative and leading-edge research. The new standard no longer limits the Superfund remediation goals to minimizing risk and controlling the migration of contaminants, but rather goes further by attempting to convert highly contaminated areas into functioning ecosystems. This paradigm shift may also involve some radically different approaches, including relying less on cutting-edge technology and looking more to nature for solutions (US EPA, 2009 c).

Case Study: The Lehigh Gap Nature Center/Palmerton Zinc Pile Superfund Site

The Lehigh Gap is a stunning geological structure where the Lehigh River flows through the Kittatinny Ridge, part of the Appalachian Mountain Range in Pennsylvania. It is the crossroads of two national trail systems, the Appalachian Trail and the Delaware and Lehigh National Heritage Corridor. The river has great historic significance, as it played an essential role in the rise of the Industrial Revolution in this country. Today the river also is important for a number of recreational uses. The region is rich in cultural and natural history, and the watershed is important for a large population between the Lehigh Gap and Philadelphia. But more than 2,000 acres of the mountainside are also a part of the Palmerton Zinc Pile Superfund Site.

Beginning in 1898, zinc smelting operations in the neighboring town of Palmerton emitted staggering amounts of sulfur dioxide and heavy metal particulates (Water Environment Federation, 2000). The resulting acid deposition destroyed vegetation, and the heavy metal deposits prevented regrowth of vegetation or soil microbes for several miles along the mountainside. Eventually, all forms of life disappeared from the mountainside, including soil microbes.

The area once touted as a tourist destination because of its beauty became a barren landscape and posed significant risk to humans. The loss of vegetation resulted in severe erosion, and much of the soil and metal contamination moved down the Lehigh River towards the Delaware Bay. Environmental scientists and engineers worked to mitigate the surface runoff of toxic metals. Highly engineered attempts to revegetate the mountain were partially successful, but did not result in diverse plant life or high-quality habitat—the new standard for ecological reuse.

In 2004, I was about to embark on a mid-career change to a new institution (Moravian College in Pennsylvania). I had been asked to chair the biology department, which itself needed revitalization in terms of updating the curriculum and enhancing the culture of scholarship. I had also just become a co-principal investigator on an NSF Undergraduate Research Center pilot grant, the goal of which was to develop a consortium of faculty and students at seven institutions to promote greater interest among students in plant science.

Living near the Palmerton Superfund site, I knew that there was a new effort to revegetate the area and stabilize the contaminants, a form of phytoremediation. Figuring that this would make a wonderful field trip for participants in our consortium, I approached the director of the project and of the new Lehigh Gap Nature Center and wildlife refuge, Dan Kunkle, a former high-school science teacher. That initial visit and subsequent tour of the site prompted by the NSF-URC grant has subsequently led to wonderful partnerships and collaborative research that has transformed not only a mountainside, but also an academic department.

Those of us at Moravian College did not come up with the idea of using natural solutions rather than engineered ones in which native metal-tolerant, warm-season grasses were used to initiate the revegetation efforts. However, several of our faculty members and students have become intimately involved with research projects aimed at re-establishing a flourishing ecosystem at the site, monitoring succession, and doing bio-inventories. They have acquired data that is used to develop both the adaptive management plan for the site and policies for the ongoing monitoring and revitalization at the rest of Palmerton Superfund site, and perhaps at other sites across the country. Given the lack of other models or examples in the ecological or restoration literature for developing healthy habitat and biodiversity at Superfund sites, we are blazing new trails – both figuratively and literally since this site is now a popular recreation and education site.

Specific projects include succession monitoring and habitat-enhancement projects; studies of the biochemical stresses and adaptations in primary colonizers that take up high levels of metals; studies of herbivory and movement of the metals in the food chain; studies of the return of a soil microbe population; bird and insect surveys and preliminary cataloging of other species returning to or migrating through the site; analysis of water quality in ponds on the refuge and the Lehigh River, through monitoring of metals in sediments and determining aquatic macroinvertebrate diversity; and monitoring of invasive species. Recently, a Moravian student completed an exhaustive bibliography of the entire history of the Lehigh Gap, which will provide a valuable resource for the community, researchers, and others.

Moravian College and the Lehigh Gap have another intriguing common link. In the 1740's, the Moravian settlers founded the school that became the college and their missionaries went through the Lehigh Gap. Their archived travel diaries may hold clues to the natural history of the area long before the zinc smelting operations and industrial revolution began. The future research opportunities exploring this history clearly extend beyond the sciences.

Moravian College has taken the lead in organizing a consortium of researchers at a dozen other partnering colleges and universities, as well as a number of state and federal agencies involved in some aspect of the revitalization of the Lehigh Gap. State and federal funds are supporting much of this effort, and the site recently also received funding from the Audubon/Toyota Together Green program. The latter is a project that brings together the local Audubon chapter and community and college volunteers (Audubon, 2009).

The Department of Biological Sciences at Moravian College now routinely takes classes to the Nature Center/Superfund site for field trips and class-based research projects. Not only are biology and environmental-studies majors benefiting from this unique outdoor laboratory, but so are students in science courses that are required as part of the liberal-studies curriculum. We have developed a new Conservation Biology and Ecological Restoration course in partnership with the Lehigh Gap Nature Center, and students in the premiere offering of course participated in the experimental design for Together Green projects. Those studies of habitat enhancement and deer exclosures are now being implemented.

Our intimate involvement with the Lehigh Gap has generated new enthusiasm that did not exist in the department five years ago; this has motivated other colleagues to become engaged in research projects with students. Over the past year, the department has acquired two significant grants, the first in a long time. Faculty are involved with K-12 teacher workshops in conjunction with the Lehigh Gap Nature Center and, along with some of the research students, serve as mentors to a youth naturalists group, whose members are also involved in authentic research at the site. These young people were recently recognized by the National Audubon Society (Cosier, 2009).

This exhilarating partnership between citizen scientists, an academic department, other campuses, state and federal agencies, and the local community has demonstrated that innovation, optimism, and careful observations of nature can lead to solutions to major environmental problems that are truly transformative. Instead of being behind a chain link fence, this site is now open to the public for research, education, lessons in a new era of conservation, and recreation.

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Supporting Potentially Transformative Research: The Administrator's Perspective

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Faculty members at predominantly undergraduate institutions (PUIs) have won external funding for potentially transformative research projects, and many of them have been remarkably successful in advancing the nation's scientific endeavors. Many of these faculty members, though not all, are at institutions that formally espouse a "teacher-scholar model" for faculty endeavors. From our experiences in contributing and/or supporting such faculty endeavors, we offer the following thoughts and insights.

Supporting and Promoting a Scholarly Culture

To provide the optimal conditions for faculty members at predominantly undergraduate institutions (PUIs) to engage in potentially transformative research and to win funding to support their transformative research, their institutions must create and sustain a culture that embraces and supports deep, ongoing scholarly inquiry by their faculty members and opportunities for intensive and extended student engagement. In short, PUIs must embrace the teacher-scholar faculty model in all of its nuances and richness. In such a culture, faculty members can maintain both high quality (active and engaging) teaching and productive research programs that involve undergraduates. And these faculty members are able to integrate their teaching and research into the fabric of their academic lives.

Engaging undergraduates in authentic scholarly work often provides faculty members fresh insights to research questions. The need to carefully explain research issues to less-expert collaborators and the opportunities to hear students explain them to each other guide faculty members to new understanding. In fact, for many faculty members, undergraduates facilitate the pursuit of research and scholarly questions that allow the faculty members to maintain their professional expertise, enthusiasm, and scholarly engagement. In particular, many faculty members at PUIs only have opportunities to work as mentors or collaborators when they work with undergraduates. In return, the undergraduate researchers become junior colleagues and scholarly collaborators in the truest sense (Osborn and Karukstis, 2009).

Creating an institutional culture at a PUI that supports scholarly inquiry by both faculty members and students is greatly enhanced and facilitated when senior and junior faculty members and administrators share an understanding of undergraduate research. Several definitions of undergraduate research have been proposed and are variously used throughout academe. A generally accepted definition and one that has been adopted by the Council on Undergraduate Research (CUR) is the following: "Undergraduate research is an inquiry or investigation conducted by an undergraduate in collaboration with a faculty mentor that makes an original intellectual or creative contribution to the discipline" (Wenzel, 1997). This definition encompasses all modes of research from both disciplinary and interdisciplinary fields, recognizes the importance of a teacher-scholar model for participating faculty members, and ensures that both faculty members and students have a vested interest in the research and its outcomes. To expand on the definition cited above, Osborn and Karukstis (2009) have articulated four unifying features that characterize undergraduate research: mentorship, originality, acceptability, and dissemination.

Why Should the Faculty at PUIs Engage in Transformative Research?

The National Science Board (2007) defines transformative research as "research that has the capacity to revolutionize existing fields, create new subfields, cause paradigm shifts, support discovery, and lead to radically new technologies." The key to promoting transformative research at PUIs involves creating an institutional infrastructure that provides opportunities for high-quality, potentially transformative research to take place. This requires two parallel investments: 1) what institutions do now to ensure that faculty members will be able to secure funding to support their research, and 2) what they need to develop as longer-term strategies that will ensure that they continue to support potentially transformative research in the future.

Faculty members are the central asset of our institutions. Without them the educational enterprise would not exist. A hallmark of a great institution is faculty members who are engaged in successful, innovative scholarly and creative work that complements and enriches their teaching. This work serves to expand knowledge; allows faculty members to develop professionally and engage in their disciplines; educates students at all levels; attracts research funding from government agencies, private foundations, corporate sponsors, and private donors; and increases the stature of the institution through having this work known locally, nationally, and internationally.

For faculty members at PUIs, a significant component of that scholarly and creative work also involves undergraduates. Undergraduate research experiences have long been a component of science programs, especially at PUIs. However, the Boyer Commission's 1998 report, *Reinventing Undergraduate Education*, helped to bring the values of undergraduate research to national prominence and underscored the importance for undergraduates in all disciplines of becoming "an active part of the audience for research." Similarly, Project Kaleidoscope highlighted the importance of a research-based curriculum and research experiences as among the best practices in undergraduate science education (Project Kaleidoscope 1991).

More recently, reports from the Association of American Colleges and Universities (2007), the Council on Competitiveness (2005), the Business Roundtable, et al. (2005), and the Business-Higher Education Forum (2003) have called for changes in education that "create life-long learners," "encourage learning through more interaction and individualization," "increase the retention rate of undergraduates…." and "promote an innovation-oriented culture while maintaining a commitment to creating new knowledge…" The authors of those reports conclude that student engagement in undergraduate research yields an array of greater educational outcomes in comparison with those of students who do not participate in these experiences. These gains are broadly related to cognitive and intellectual growth, professional growth and advancement, and personal growth (Osborn and Karukstis, 2009). And Osborn and Karukstis (2009) have described specific gains in these areas that are attributed to participation in undergraduate research. For example, an undergraduate research experience has been shown to be an effective tool for enhancing retention (Nagda et al., 1998; Ishiyama, 2002); career preparation (Mogk, 1992; Ishiyama and Hopkins, 2002; Seymour et al., 2004); increasing interest in learning (Lopatto, 2003, 2004, 2006; Tomovic, 1994); and a sign of excellence among academic programs (Doyle, 2000). Moreover, undergraduate research offers high levels of academic challenge, fosters active and collaborative learning, builds from student-faculty interactions, and contributes to a supportive campus environment. All those activities are known to be high-impact educational practices (Kuh, 2008). Therefore, for PUIs, having faculty members who are engaged in potentially revolutionary scholarly work has an even greater impact on undergraduates: strengthening their educational outcomes and in enhancing their motivation to persist and join the next generation of scientists.

Administrative Strategies to Promote Transformative Research at PUIs

Faculty Time

Nationally, the integration of research into the curriculum has progressed from its beginnings in the mid-1980's. Research-active faculty members have been key players in this curricular change, as their scholarship has served as the engine for innovation. As demonstrated by Karukstis and Elgren (2007), building research-rich/research-supportive curricula makes sense pedagogically. Students learn more about how science is done and practice the critical reasoning skills essential to scientific research, and the learning they do is more engaging and fun. Incorporating authentic research into individual courses and into curricula also makes sense for the faculty members. In particular, developing learning experiences that align with and incorporate the faculty member's scholarship can be very cost-effective and time-efficient. "Teaching laboratories" are often easier to support (with both financial and staff resources), students learn skills necessary to participate in independent research in the faculty member's laboratories, and students take over much of the preparation work, which provides the faculty member with needed time to engage in scholarly work and to use for other activities.

The Howard Hughes Medical Institute is currently supporting two multi-institutional initiatives that seek to understand and promote curricular-based research opportunities as a way to enhance learning. These initiatives are the nationwide phage genomics research program and the Classroom Undergraduate Research Experiences (CURE) survey. Thus far, the results from CURE are providing evidence that classroom research-like activities will lead to significant learning gains; as expected, the gains are less pronounced than a full-fledged summer research experience, which was determined from the Summer Undergraduate Research Experiences (SURE) survey. (Lopatto et al., 2008).

Administrators can support faculty members' efforts to realize the teacher-scholar model by proactively encouraging them to efficiently utilize their academic time (e.g., number of office hours, open-door policies, number and type of course assignments, number and type of committee service, etc.), thereby ensuring that the faculty members have regular time to actively engage in research, preferably that which involves undergraduates. A number of useful strategies for effective time management for the teacher-scholar model were published in the June 2004 issue of the Council on Undergraduate Research's *CUR Quarterly*, which focused on "Creating Time for Research."

Tenure and Promotion Criteria

One of the most important components of a tenure-track faculty member's first few years is preparing for formal evaluation process. The standards for evaluating faculty performance are typically outlined in an institution's reappointment, tenure, and promotion criteria. Those criteria guide the way that faculty members should approach their scholarship, teaching, and other key facets of academic work (e.g., academic advising, service, etc.). Most tenure and promotion criteria are either included within faculty handbooks or exist as stand-alone documents, and the criteria are usually articulated to prospective faculty members as they progress through the interview and appointment processes and the criteria are usually revisited as new faculty members begin their tenure-track appointments. Many PUI's have tenure and promotion criteria that stress excellence in teaching, balanced with excellence in some form of peer-reviewed scholarship; often service is required as well. The range of acceptable scholarship varies from institution to institution, but the most common expectation is that faculty members will contribute actively to the broader intellectual community. Those contributions necessarily involve the "sharing of results with the professional community" (Illinois Wesleyan University Faculty Handbook), which is often done in the form of peer-reviewed publications. Typically, faculty members must show active engagement within their discipline or field in order to "extend the boundaries and/or refine the subtleties of interpretation," as the Illinois Wesleyan handbook also puts it. According to many faculty members navigating the processes toward tenure, an important difficulty with their institutions' tenure and promotion criteria is that many criteria do not specifically define the desired number and/or significance of publications, including the journals or other venues that are deemed "acceptable" by departments and/or tenure and promotion committees. This leaves the pre-tenure faculty members, departments, and/or tenure and promotion committees with the task of interpreting institutional standards on a case-by-case basis. Most tenure and promotion criteria do not explicitly address how to evaluate scholarship that would be defined as high-risk, and high impact, which might lead to fewer publications in the short run, causing many early-career faculty members to feel that a "safer" research program that results in multiple publications by the time of the tenure review is the only acceptable path for their research plan. Thus, many early-career faculty members conduct low-risk, "traditional" research that will have greater productivity as measured by publication in respectable peer-reviewed journals. This often discourages these faculty members, who are in highly productive and creative years of their careers, and it deters them from pursuing potentially transformative research questions, which usually have higher risk and lower measurable productivity in terms of publications, at least at first.

One of the most important aspects, then, of providing pre-tenure faculty members with the option of pursuing transformative research is to ensure that tenure and promotion criteria support high-risk, but potentially high-impact, research. Many institutions already have criteria that are quite broad; however, they need to be more explicit about supporting high-risk research as a type of scholarship allowable for attaining tenure and promotion.

If institutional administrators want to foster opportunities for potentially transformative research, especially for pre-tenure faculty members, then administrators must facilitate the discussion and revision of the tenure and promotion processes and criteria to include avenues for early-career faculty members to pursue high-risk research. This includes leading faculty discussions and adopting policies that broaden institutional processes and tenure and promotion criteria. In particular, processes and criteria need to be modified to recognize and reward the following: 1) non-traditional funding sources, 2) non-standard dissemination venues, 3) interdisciplinary scholarship, 4) mentoring of pre-tenure and pre-promotion faculty members, and 5) education of departments and tenure and promotion committees about effective mechanisms to evaluate faculty members conducting transformative research. We discuss each of these topics below.

Non-traditional Funding Sources. One issue that arises with pre-tenure faculty members working on any scholarly project, including those that are high-risk, is finding financial support for high-quality research. Indeed, as a first step, institutions need to do a better job of assisting all faculty members, including early-career faculty, in becoming more effective in procuring external funding and in disseminating the results of the resulting research in appropriate peer-reviewed venues. Much has already been written about ways of supporting faculty efforts to obtain external grants from government agencies, private foundations, and alumni (see, for example, Bolek and Forsythe, 2008; Graham and Johnson, 2004; Watson, 2004; Zack and Dickinson, 2004; Giese, 2004; and Kinnard, 2004). However, external funding for potentially transformative research may need to come from entities that have not been traditional sources for a particular institution or department. In particular, funding may need to be sought from for-profit entities, including corporations, venture capital investors, and even from individuals. Administrators need to make sure each faculty member understands the necessity and importance of working with their institution's advancement or development office as they plan to approach non-traditional funding sources. Development personnel can provide invaluable support in identifying potential donors who might be interested in funding a project not yet recognized by federal funding agencies. Likewise, personnel in the development office are knowledgable about local, state, and regional private foundations, corporations, and economic-development initiatives that might be fruitful sources of funding for potentially high-risk projects. It is important, however, to understand ahead of time that these funding sources may insist on establishing non-disclosure agreements that may restrict reporting of results or funding amounts, which may be important to faculty members' ability to include such work in their tenure files.

Administrators also need to be vigilant in their efforts to provide faculty members with key resources for grant-writing. Such resources include:

- Having a person on staff who assists faculty members in developing (and in some cases writing) grant proposals (e.g., an office of sponsored research);
- Providing a set of databases available to faculty members that allows them to search for funding opportunities;
- Offering proposal-writing workshops on-campus, and/or providing support for faculty members to attend off-campus workshops;
- Allowing buy-out of some of the normal teaching responsibilities with grant funding;
- Developing institutional indirect-cost policies that encourage grant-writing;
- Using indirect funds in support of faculty research;
- Recognizing peer-reviewed grants and well-reviewed grant proposals (even when not funded) as one part of the suite of faculty work that is counted for tenure and promotion; and
- Appointing as department chairs faculty members who embrace the teacher-scholar model and who present strong records of research and grantsmanship.

Those are just a few ways to provide grant-proposal-writing support for faculty members. Administrators can also acknowledge faculty members who have been successful in obtaining external funding in a public manner, whether on the university Web page, to trustees, to other faculty members, or by hosting recognition receptions. Only after a campus has established a culture that encourages and rewards pursuit of external research funding can that institution can take the next step of recognizing and rewarding non-traditional forms of funding.

Acknowledge Non-standard Dissemination Venues. Another major obstacle for pre-tenure faculty members who pursue high-risk research is that no precise or standard methods have been established for evaluating either funding obtained from non-traditional sources or research results disseminated in non-standard venues. Thus, in addition to establishing a culture of active faculty scholarship, which includes successful grant seeking and production of peer-reviewed journal articles, institutions will need to determine methods of evaluating and measuring scholarly success via non-standard venues. Even though the ultimate goal must remain the generation of peer-reviewed publications, research that is asking potentially transformative questions may initially result in dissemination in such venues as the following:.

- A report to a funding source or a regulatory group;
- Contributing to (and perhaps even organizing) a summit or symposium that results in a proceedings or edited volume;
- Publication in the "gray literature/venues," such as open access, online-only journals, influential blog sites, etc.; and
- Publication of "null" results.

The methods of evaluating a faculty member's scholarly work must be determined by each institution, reflecting the culture and expectations at that institution. However, so that the standards for tenure and promotion remain robust, the methods established for evaluating non-traditional work should follow methods similar to those used to review more "traditional" faculty productivity, and the methods should be based on fundamental principles that characterize any form of high-quality research. {For example, a tenure candidate may have been contributing to an influential blog site, and the candidate's entries may have included original results, as well as robust contextual synthesis; and the blog entries have attracted the top scholars in the field, who have provided vibrant peer-review and feedback on the candidate's work, which have in turn drawn the attention of many more scholars to the site. As a consequence, this outlet has brought significant recognition to the candidate's scholarly work and to the institution.}

Additional review and validation of research that is disseminated in new, non-traditional venues could be added to the reappointment, tenure, and promotion process. Here, a set of external reviewers could be used to evaluate non-traditional forms of funding and dissemination. Many institutions already rely on a set of letters from independent, external evaluators for the summative tenure and promotion reviews. Such external reviewers could also be used in the intermediate years to provide formative feedback. As an institution develops these methods, pre-tenure faculty members who indicate that they will be pursuing high-risk research will need to work with their departments and the central administration regarding the methods that will be used to evaluate their work. Furthermore, tenure and promotion committees will need to understand the collaborative nature of scholarship that often occurs in high-risk research. As for traditional faculty scholarship, publications with multiple authors should "count" the same as single-authored work. This may mean that pre-tenure faculty members and their collaborators will need to describe their contributions to each publication. However, meaningful collaborations are vital to much of the research currently being pursued in the sciences.

Many of the same suggestions discussed above regarding administrative support for securing external resources can be used to encourage publication of scholarly work. Does an institution have faculty-development funds to support research leading to publications? Are there pre-tenure leave options that allow faculty members to spend one or two semesters pursuing their own scholarship (in addition to regular sabbatical leaves for tenured faculty members)? Is the scholarship of pre-tenure faculty members recognized in a public manner (such as at a faculty scholarship recognition event)?

Interdisciplinary Research. In many cases, potentially transformative research will involve interdisciplinary or multidisciplinary collaboration. Historically, in fact, significant developments have come from collaborations among investigators working in seemingly disparate fields. For example, the harnessing of atomic energy in the late 1930s and 1940s occurred as a result of physicists, materials scientists, and engineers working together. More recently, the field of bioinformatics has grown out of the human genome project and has brought together molecular biologists, mathematicians, and computer scientists. Nanotechnology has grown from knowledge about of carbon buckeyballs and is a relatively new discipline that embraces chemistry, materials science, and molecular biology, among other fields.

Clearly, there have been many attempts by governmental and private agencies and organizations over the past 15 to 20 years to steer the academy toward preparing scientists for the future by "encouraging" changes in the academic culture to foster collaborations and promote interdisciplinary training (e.g., National Research Council, 2003; National Institutes of Health, 2004; National Science Foundation, 2009; Association of American Medical Colleges and Howard Hughes Medical Institute, 2009).

While interdisciplinary research has attracted much attention and has been growing, institutional cultures and tenure and promotion processes have been slow to change (e.g., Hurtado and Sharkness, 2008; NSF, 2009). The NSF's 2003 *Characteristics of Doctoral Scientists and Engineers in the United States* indicated that between 42 and 51 percent of those employed in the biological and natural sciences were over 50 years old and that between 34 and 44 percent were more than 20 years past receiving their doctorates. These data indicate that the academy may see a large turnover of science faculty members within the next decade and a half (NSF, 2006). What will our new colleagues want in an institutional home? In recent years, new faculty members have wanted facilities that will allow them to continue the types of work they have done in the past, collaborations with new colleagues, and opportunities to teach upper-level courses within their disciplinary and interdisciplinary specialty areas. They also want these efforts to be recognized and rewarded. Meeting these desires will require PUIs to provide modern research spaces that afford opportunities for the cross-fertilization of ideas from multiple disciplines; on-site collaborations both within and across disciplines; the ability to teach cross-disciplinarily; and tenure and promotion processes and criteria that clearly recognize interdiscipinarity. These approaches are not currently found in the majority of PUIs, which still predominantly feature a departmental-silo culture. Administrators must encourage and facilitate the creation of new cross-disciplinary collaborations for both research and teaching if PUIs are to attract and retain excellent faculty members in the future.

How can administrators encourage and facilitate the creation of new cross-disciplinary collaborations for both teaching and research? Key ingredients are time, opportunity, and incentives to push interactions toward collaborations. Time is self-explanatory, in that people need time to exchange ideas, learn to speak a common language, and develop collaborative projects or courses. Opportunity will require changes in facilities design since many of our institutions are still organized around departments that are segregated from one another, with chemistry on one floor, biology on another, and perhaps math and computer science in a separate building across campus. Industrial labs are typically designed to keep the exchange of ideas flowing among researchers with varied interests, for example, through open labs, common library space, huddle rooms, breakout spaces, spaces for small conferences, etc. While many of our campus buildings do not incorporate these concepts, it is possible to create areas that foster collaborations by grouping faculty members by areas of interest. For example, a neuroscience area might include cognitive scientists, cell and molecular biologists, biochemists, psychologists, etc. Or faculty members might be grouped based on their needs for the same types of instrumentation (for example, gas chromatographs with or without new spectrometer facilities– would be needed by plant biologists, environmental toxicologists, chemists, biochemists, etc). By placing people with different backgrounds in close proximity (and ensuring that they have the time to interact), daily communications will ultimately lead to new ideas for investigation. Likewise, these interactions will lead to novel teaching approaches that integrate fields, thus helping to better prepare our students for what they will encounter in graduate and professional schools and the workplace.

Incentives also can encourage these interactions. Effective ways of encouraging and promoting the importance of cross-disciplinary work include administrative support for mini-grants to provide funds for supplies needed to collect preliminary data; a rotating semester-long reduction of teaching or service tied to expected outcomes, such as a grant proposal or a new cross-disciplinary course to be taught the next semester; dinner meetings to encourage cross-disciplinary discussions; or a cross-disciplinary speakers series to excite faculty members and students about potential areas of investigation. For more information and suggestions concerning ways to bring about more collaboration, see Kezar and Lester (2009).

Mentoring. One of the most important responsibilities of an institution (and the responsibilities of department chairs, deans, and chief academic officers) is mentoring pre-tenure faculty members. Many institutions hold workshops on the tenure and promotion process for pre-tenure faculty members and their supervisors. These workshops describe the criteria for tenure and promotion and include opportunities for faculty members and their supervisors to ask questions. An advantage of being on the faculty at a PUI is that pre-tenure faculty members are often the center of attention of department chairs, deans, and provosts. Pre-tenure faculty members at most PUIs receive several forms of feedback from multiple evaluations (at both the departmental and institutional levels) during the years leading up to the summative tenure-review year. Each pre-tenure faculty member should be encouraged to develop a plan and general timeline for strategically advancing an overall scholarly program, whether the faculty member is engaged in high-risk, potentially transformative research or in more traditional research. In particular, a pre-tenure faculty member interested in pursuing high-risk research needs to be encouraged to follow that line of research, but each faculty member also needs to hear the message, if it is required by institutional culture, that in addition, the research program should include some projects that are more likely to lead to the type of peer-reviewed publications commonly recognized by their departments and by the promotion and tenure committees. It is good advice for any pre-tenure faculty member to have multiple threads (or projects) that comprise an overall research program. This strategy mitigates problems that may arise from "putting all of your eggs in one basket," especially important for those engaging in high-risk research. However, with multiple projects under way, there is also a risk of pre-tenure faculty members becoming "spread too thin" and not bringing any of the research to fruition in peer-reviewed venues. The message about what is required to achieve tenure and about the different research strategies can be shared in informal mentoring sessions with senior faculty members or through more formal letters from the department, tenure and promotion committee, or an administrator during the evaluation process in the early years of a faculty member's probationary period. The message also should be included in the institution's tenure and promotion standards.

Educating Tenure and Promotion Committees. Administrators can also play a leading role in educating departmental and institutional tenure and promotion committees about the value and the unique aspects of transformative research. Tenure and promotion committees also should be made aware of the challenges associated with high-risk, potentially transformative research—such as delay in publishable results, non-traditional funding sources, and dissemination of results through non-standard publications and presentation venues. Faculty members who engage in potentially transformative research will need to carefully describe the progress they are making relative to their scholarly agendas and they must provide evidence of their progress, such as industry reports, a description of scholarly presentations, patents, and other relevant documents. It is particularly important that pre-tenure faculty members understand the expectations for appropriate materials and documentation to include in their dossiers as they progress through the tenure and promotion process. The tenure and promotion committee should regularly provide clear feedback to the pre-tenure faculty member regarding progress toward tenure and promotion. This feedback allows the faculty member to make modifications to the research agenda and/or to provide further evidence of the progress unfolding as the tenure evaluation approaches. Finally, if a pre-tenure faculty member describes high-risk research that may not produce results by the time of the tenure review, which normally occurs in the sixth year of employment, administrators might want to initiate discussions about options for extending the tenure clock. These options need to be considered carefully to ensure that national standards are being followed (e.g., those of the American Association of University Professors).

Finally, administrators have great responsibility for supporting and guiding pre-tenure faculty members as they progress through the reappointment and tenure process. Administrators can use their positions of leadership to promote potentially transformative research by early-career faculty members through support for individuals and mentoring of the promotion and tenure committees. Administrators also need to reduce the anxiety of the early-career faculty members and provide opportunities that allow these faculty members to be successful scholars. Colleges and universities can expect great results if these suggestions are followed as these faculty members become permanent members of the scholarly community.

Merit Considerations for Mid-Career and Senior Faculty Members

Mid-career and senior faculty members often have much more freedom to pursue non-traditional forms of scholarship, since attaining tenure and promotion often relaxes the intense pressure to publish quickly. This allows these faculty members to pursue lines of research that may not have the same impact or immediate results required for the tenure decision. However, since many tenured faculty members face post-tenure reviews and merit-pay considerations that include evaluation of their scholarly work according to standards and criteria similar to those used for tenure decisions, steps should be taken to ensure that these reviews also do not inhibit innovation and high-risk, potentially transformative research. Mid-career and senior faculty members should be rewarded for pursuing high-risk research, as well as for more traditional lines of research. Many of the resources for supporting transformative research discussed in the previous section also can be applied to mid-career and senior faculty members conducting high-risk research (e.g., determining mechanisms to evaluate high-risk research, encouraging faculty members to concurrently pursue traditional and high-risk research, and providing an environment that encourages and supports scholarship and grant seeking).

Administrators have many ways to encourage and support mid-career and senior faculty members who choose to pursue high-risk, high-impact research. One way is by providing seed money for projects that are not yet ready for external support. A number of external funding sources provide start-up grants for early-career faculty members, but those same opportunities are not available for mid-career and senior faculty members. Seed money can come from a number of sources, such as institutional faculty-development funds, money donated to support pilot projects, or indirect funds generated by funded research grants. Institutional support for new avenues of scholarship by mid-career and senior faculty members can lead to projects that have potential for external funding.

Another important step in promoting high-risk research is to encourage mentoring and collaborative relationships among early-career and mid-career or senior faculty members. The energy and creativity of new faculty members often can be infectious. Encouraging faculty members to team-teach courses on "big ideas" can lead to stimulating discussions beyond the classroom and to links among faculty members that might not otherwise have occurred. Creating an atmosphere of intellectual stimulation and risk-taking in the classroom can often translate into fruitful scholarly collaborations. Other information about ways to nurture collaborations among faculty members has already been discussed. The end result of creating an environment supportive of successful mid-career and senior faculty scholars is that the institution becomes a thriving intellectual center.

Promoting Entrepreneurial Approaches to Fundraising

Most would agree that an underlying goal of any academic institution is to educate students in such a manner as to inspire a passion for knowledge that will enable them to enrich and transform their chosen disciplines. It is the responsibility of academic institutions to prepare students for leadership in a global society, and thus our new generation of scientific researchers must be well versed in new technologies. This is not an easy task when we are currently experiencing static or declining federal research funding from large agencies such as the National Institutes of Health and the National Science Foundation, along with rapidly changing technology, declining student interest in scientific fields, and growing outsourcing of jobs from the United States. Thus the role of an administrator must include finding alternative ways to fund STEM (science, technology, engineering, mathematics) fields. One way to accomplish this task is to make the pursuit of STEM education and research more fun, exciting, and relevant to commercial entities. To do this, administrators should support and encourage potentially transformative research by creating environments that promote excellence in applied, as well as basic, research; they should empower faculty members to pursue promising new programs and funding initiatives from private as well as public sponsors.

If administrators expect that an area of potentially transformative research might lead to scientific and technical applications, they need to encourage and support development of policies and arrangements to manage the intellectual property rights that will be a natural outgrowth of inventions and discoveries from this research.

Let us first review the differences and similarities between academic and commercial intellectual property arrangements. In employment law, the relevant statutes say that work produced by employees as part of their employment is the property of the employer (the so-called "work for hire" statutes). In industrial or other commercial employment settings, the discoveries of a scientist and the relevant patents devolve to the employer, who might arrange for certain rights or incentives to be provided to employees as partial supplemental compensation for their creative contributions. However, in academia, it is a long-standing principle that scholarly work produced by faculty members will remain the intellectual property of the faculty member; hence it is the faculty member, not the institution, that typically is asked to sign copyright agreements with publishers for books and articles. Most institutions implicitly, if not explicitly, assign the intellectual property of such printed products as books, articles, class syllabi, class Web sites, class assignments, and personal (professional) Web pages to the faculty member, while reserving the intellectual property rights to policy materials, departmental documents, the results of committee work, or the administrative work for the department or institution.

Most institutions concede that institutional investments during the academic year, intervening summers, and during sabbaticals, do not merit retaining rights to commercially successful textbooks or monographs. In simpler days, institutions retained intellectual property rights to the outcomes of academic research only for products benefitting from substantial ***institutional*** investment and likely to bring substantial returns from commercialization. This approach once applied largely to products with viable patent possibilities, but in some cases this approach now also applies to software with commercial possibilities. Further, institutions investing in online courses for revenue purposes often retain the rights to those online instructional products. Since all of this has become more complex, it behooves each institution to assess its priorities and to clearly state in advance its interests in the results of the academic work of its employees. And while this may seem oppressive in the normally free and open academic environment, it is commonplace, and employers' rights to work-for-hire are the default under law. Hence institutions can establish a broad sense of good will and shared enterprise with their faculty members by affirming in their intellectual property policies that the traditional instructional and scholarly work products of faculty members are retained by the faculty members (by stating that the institution relinquishes its rights to those products).

Having an invention and patent policy ensures that discoveries and inventions created by members of the university community (including but not limited to faculty members, staff members, and student employees) are shared, utilized and disseminated effectively. It is the responsibility of the institution as the employer to assist its faculty members and staff members in properly disclosing their scholarly work to ensure that commercial benefits are not lost and to ensure that the commercial benefits are shared in an equitable manner, such that the outcomes benefit and recognize the contributions of both the inventor and the college or university. An intellectual Property policy (IPP) can be a valuable resource for creating a culture poised for transformative research. When correctly instituted, an IPP creates an environment of cooperation and trust. The goal of an IPP would be to offer a system of support for the development of innovative materials that benefits both the inventor and the institution with fair and equitable distributions. An IPP should be viewed by faculty members and the institution as a tool of empowerment.

Developing an Intellectual Property Policy Agreement (IPP)

When instituting an IPP, it is imperative that close attention be given to the structure and content of the policy. Of first importance is to clearly define what constitutes an invention or intellectual property of mutual interest to a faculty member and the institution; who is responsible for administering the policy; and to whom this policy is applicable.

In terms of intellectual property, inventions may include such things as ideas, programs, discoveries, processes, and more, whether patentable or unpatentable. Thus, it is necessary to clearly define the institution's definition of invention. Secondly, research and discovery at an academic institution may involve an array of participants that includes students, staff members, postdoctoral fellows, tenured and pre-tenure faculty members, and visiting faculty members. It is beneficial to all participants involved if the institution's IPP clearly defines the audience for which the policy is applicable. For example, if a visiting professor is conducting research at an institution other than her home institution and makes a discovery, is she subject to the IPP of the institution that she is visiting or to the policy of her home institution? Does this decision change depending on whether she is receiving any financial support from the institution being visited? To avoid unpleasant disagreements or unwelcome surprises, an IPP should include an explanation of the applicability of the intellectual property policy.

Once the institution has determined what constitutes an invention, and which people and activities would be subject to its IPP, it is important to define who is responsible for administering this policy. This administrative group or committee should include representation from key areas in order to best aid the college and the researcher in maximizing the potential of an invention. The goals of the committee would include evaluating the patentability and commercial value of the patent, as well as aiding in determining a course of action for commercialization of the invention. The committee should also be utilized to oversee the commercialization of the invention in order to ensure just financial rewards for the college and the inventor. With these goals in mind, it is advantageous for this committee to report to either the president or provost (chief academic officer) of the institution. The committee itself should include a senior academic administrator such as the provost or vice president for academic affiars, a senior financial administrator such as the chief financial officer, and the dean of the relevant academic unit, as well as any other members of the college administration with experience or training relating to invention and innovation. To build confidence that it will protect faculty interests as well as institutional interests, the committee should also have senior faculty representatives. In order for the IPP to be viewed as empowering, it is important that the policy, as well as the process, be supported at the upper levels of administration, including the provost, president, and the board of trustees and by senior faculty members and faculty committees. Lastly, it is imperative that this committee has access to an experienced intellectual-property attorney for consultation on all legal matters pertaining to the policy.

Ownership. Ownership is key in the application of an intellectual property policy and this should be clearly defined. Scientific discovery usually comes about through the merging of many resources. These resources might include the intellect and work of the inventor, work of a collaborator(s) at another institution, work of students or other employees of the inventor and the college, the financial resources of the college (either directly or through use of space and instrumentation), and, often, financial funding from the public and/or private sector. Thus, it is important for these varied contributions to be considered and for ownership to be clearly defined before the work begins. The IPP of an institution should clearly address the issue of ownership in relation to all conceivable scenarios of multiple contributors to the outcome.

Reporting. If the goal of an IPP is to assist faculty members and staff members in disclosing their scholarly work, and to ensure that the commercial benefits are recognized and shared in an equitable manner that benefits and recognizes the contribution of both the inventor and the institution, a clearly delineated process for reporting an invention is necessary. Timeliness plays a large role in the marketability and commercialization of an invention. It is important that the invention be promptly reported through patent disclosures and patent applications as well as publications, hence the institutional committee process the invention in a timely manner. The time frame for this process should be defined, in order to ensure that all parties involved act within an appropriate and judicious time frame that would allow maximizing the commercialization potential of the invention. Outlining a specific time frame and process for reporting and developing the invention will have a large impact on the potential commercial rewards of the invention.

Financial Considerations. Legal expenses and distribution of income are often difficult considerations related to the application of an IPP. It is essential that the institution has legal resources and expertise readily available for the evaluation of the potential for commercialization of the invention. Because the goal of potentially transformative research is to transform, the institution must be prepared to aid in the process of commercializing the research so that it can be readily used and the benefits of the innovation are accessible. Thus, academic institutions should have ready access to patent attorneys and IPA experts. Institutions should also provide resources of time and money to enable the inventor(s) to reasonably document the discoveries and to develop the patent disclosure. It would be beneficial for the institution to use legal experts to create generic contract agreements, non-disclosure and confidentiality agreements, and material-transfer agreements in order to encourage the initial processes of innovation. To aid in developing templates for these documents, institutions should research and study the Web sites of other colleges and universities, because many examples of such policies, agreements, and contracts are available.

The process of commercializing an invention or innovation should be defined, and the responsibilities for the financial expenses that will be incurred should be clearly delineated. There must be a clear commitment from the institution to see the project through its development, and this plan must also include an exit strategy. Having a clearly delineated process and ready access to needed expert resources encourages faculty members and the institution to pursue commercialization. Again, there are many examples of excellent IPPs available on the Internet, and they are useful starting points from which institutions can begin to develop their own institutional Intellectual Property policies.

Perhaps the most-discussed consideration for an IPP is distribution of income. The goals of an IPP would be to provide a simple, fair, and equitable distribution of income. Consideration should be given to expenses incurred by the academic institution. Furthermore, after considering the expenses to the institution, any income should be distributed so that the inventor(s), the department, the division, and the institution receive fair financial shares. It is expected that the outcome of a successful innovation or invention would financially benefit both the inventor and the institution. One very important consideration is that an IPP should be a tool that encourages faculty members to pursue formal protection of valuable intellectual property. Hence, as a way to entice faculty members to protect the shared intellectual property, it is common for IPPs to define the distribution of income so that a large percentage of revenue is credited to the inventor(s) when the profit is small; as the level of profit increases, the percentage of revenue credited to the institution may increase.

Nonetheless, efforts devoted to protection of intellectual property and patent rights may slow the disclosure of the related academic work, reducing the normally available indicators of productive scholarly research. Institutions should have clear procedures for reviewing the research of faculty members who generate results that need such caution and protection.

While research universities have vested interests in asserting and protecting the value of the intellectual discoveries of their faculty members, PUIs with less of a research focus have alternatives, including alternative interests. Of greatest interest to a PUI is sustaining positive and productive relationships with its most effective teacher-scholars. Since these relationships may be strained by working out the details of agreements on particular discoveries, an alternative to asserting patent rights is for the institution to waive its rights to discoveries and to support faculty members in gaining independent advice on patents and patent protection.

A further threat from the commercialization of a faculty member's discoveries is that patent efforts or venture-capital investments can be a major distraction from the normal mix of activities of a teacher-scholar. A supportive administrator might want to offer reassigned time (perhaps purchased with venture-capital funding) to a faculty member for a period of time, providing a reduced teaching load to offset the heavy demands of pursuing a patent or commercialization project. Some colleges have even decided to invest (effectively providing venture capital) in faculty members' small-business endeavors as a sign of support and respect for innovative faculty colleagues.

In cases such as those, institutions place a premium on the relationships they build and maintain with their most innovative and creative faculty colleagues; almost without exception, investments such as those are rewarded with long-term loyalty from the faculty members the institutions most want to keep. Whether that premium is expressed through supportive IPP arrangements, relinquishing intellectual-property rights to the faculty member, or investing in commercialization endeavors, the administrators who make these commitments express an undeniable value system for the institution. While there might be financial return on investments such as these, the resulting goodwill from key faculty members may be the greatest and best reward.

Conclusion

In this chapter, we have outlined several ways that academic administrators at PUIs can support research-rich environments. Academic administrators can encourage the professional growth and development of their faculty members and establish an environment that supports potentially transformative research projects. Indeed, one of the most important responsibilities of academic administrators is supporting all aspects of the professional development of faculty members, who are the most important assets of our colleges and universities. Faculty members at PUIs have been successful at producing scholarship that is transformative and that advances the nation's scientific endeavors. With the assistance of administrators, more of this type of fundamental scientific research can be completed at PUIs, resulting in engaged and productive faculty members and a highly qualified future generation of scientists.

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Effective Collaborations to Support Transformative Research

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A challenge that faculty members at predominantly undergraduate institutions and those at larger colleges and universities often share is establishing effective and sustainable research collaborations that engage both them and their students in successful scholarly enterprises. The existence of the appropriate "intellectual ferment" within a department, a research facility, a laboratory, or an institution is a critical prerequisite to the conduct of quality research. There must be a culture of intellectual inquiry and critique, and an expectation of investigation, discovery, and debate on matters of intellectual importance. Research cultures ultimately develop within communities of peers or near-peers; while faculty at research institutions are often leaders in such communities, they should not be the only contributing members.

The labor force limitations that constrain smaller academic departments are a primary constraint on the development of a research "culture" within academic units and on college campuses generally. Hiring decisions in most academic departments are defined first and foremost by the need to meet urgent instructional needs, as opposed to considerations of building research strength in one field or another. Thus, while the cohort of faculty in a department may "cover the ground" of a discipline instructionally, there may be little overlap in their scholarly interests and thus little common ground for the kind of intellectual exchange that can lead to successful (or potentially transformative) research. The American Institute of Physics has collected data on overall research and educational productivity in physics departments nationally, and evident in these data is a dramatic up-tick in measures of research productivity (i.e., numbers of publications, grant funding, awards, etc.) when total faculty numbers exceed thirty (Muhkerjee, pers comm; data from AIP, 2009). While the particular "critical mass" of departmental faculty members necessary to facilitate high intensity (and presumably thereby, potentially transformative) research must certainly vary by discipline, it is clear that faculty numbers such as these are well out of the reach of most colleges and universities, let alone those whose missions are primarily to serve undergraduates. Thus, collaborations, especially those that in one way or another cross the boundaries of institutions and departments, are essential to producing the intellectual environment that facilitates transformative research in academic institutions generally. For faculty members at predominantly undergraduate institutions (PUI's), the challenge is to identify those collaborations that can do the most to "seed the field" for themselves, their colleagues, and their students.

In this chapter, we will describe the broad array of research collaborations that take place at a PUI, and discuss which factors can either foster or inhibit the initiation, maintenance and productivity of such collaborations. This chapter will present personal experiences and the resources that may support "extra-departmental" collaborations, with examples drawn from the reports of participants at the CUR Transformative Research Summit.

Collaborations with Faculty at Other Academic Institutions

PUI-PUI collaborations: Collaboration between faculty members at PUI's affords the benefit of shared professional experiences and (largely) shared issues with respect to time, access to resources, and institutional expectations. Summit participant and mathematician Lisette DePillis has maintained productive collaborations with several colleagues at nearby PUI's, including Pomona College and Occidental College, as well as at more distant undergraduate institutions (Murray State University in Kentucky and institutions in Washington, Australia, and New Zealand). The beginnings of her collaborations lay in shared experiences and needs (a Claremont Colleges mathematics colloquium series initiated the collaborative connections to Pomona College; The Washington State University collaboration is a continuation of a project that was initiated when her collaborator was working with her as a grant-funded postdoctoral fellow at HMC. Other collaborative connections began at disciplinary meetings and workshops, including the connections to Murray State. Once initiated, the connections are fed by frequent contact, and, as appropriate, by joint efforts to secure extramural support (for example, an NSF grant was secured via a jointly written grant proposal and supported DePillis's collaboration with Murray State University for several years).

Collaborative contact needs to be "high quality" communication: Email alone is inadequate to sustain the necessary interactions, even if electronic contact is frequent. DePillis and her nearby collaborators schedule weekly in-person conversations; more distant collaborative contacts are maintained via weekly telephone or Skype conversations. To afford their collaborative contacts the priority they merit, telephone interactions are scheduled for set times each week, and blocks of research time are deliberately scheduled into the week, to ensure that the collaborative efforts move forward despite the varied student and administrative commitments that PUI faculty members juggle. Emails as well as online "Collaboration and Learning Environment" tools such as Sakai augment the live exchanges. DePillis maintains separate written records of all her collaborative interactions, both to keep track of and to effectively support the links.

An interesting and potentially enriching collaborative option that may be more available on PUI campuses than at larger institutions is the potential to develop successful cross-disciplinary collaborations. Summit participant and computer scientist Judy Cushing developed a fruitful collaboration with an ecologist on her campus that focused on the development of information technology for ecology researchers. The project was based initially on a funded planning grant submitted by her collaborator and a jointly conducted workshop targeting both disciplines. The investigations were subsequently supported through a grant from the NSF Research at Undergraduate Institutions (RUI) program. Since then, the collaboration has focused on the barriers facing scientists when using informatics tools (including the lack of theoretical or conceptual structures that allow for data characterization) and the development and dissemination of tools.

The major lessons of Cushing's interdisciplinary collaboration include the necessity of starting small in order to get to know one's interdepartmental colleague(s) and, to a lesser extent, their discipline(s) before launching a large project. It takes time to learn enough about another discipline to converse intelligently. Further, not only are individual differences in personality and working style likely to influence the collaboration, but so also are cultural differences among disciplines, which can be both unexpected and considerable. It takes time to understand these, and it is good practice to avoid grappling with them under the pressure of major proposal or paper deadlines. A second important lesson is that it is not enough for (in this case) a computer scientist to produce an application to enhance an ecologist's biological research, or for the natural scientist to just provide data for informatics research. The collaborative project needs to make important research contributions for each collaborator and in each discipline, if the collaboration is to remain vital, and if truly transformative discoveries are to be within reach.

"R-1"-PUI collaborations: These kinds of collaborative arrangements often make sense in terms of available resources. For example, many institutions ranked as Research-Intensive by Carnegie, in particular larger state universities, often have underutilized research instrumentation and other infrastructure that can be made available to PUI faculty members and students through negotiated collaborative arrangements, with the goal of generating grant support for cooperative research projects. National Science Foundation funding initiatives provide both direct and indirect support to such arrangements (for example, the Research Opportunity Awards option in the RUI Program for PUI faculty; recommended "Broader Impacts" arrangements for the use of NSF-supported research instrumentation, etc.). Challenges in such cooperative efforts relate to the differing missions and scheduling patterns for research work on PUI and R-1 campuses, and the pressures these put on collaborating faculty members.

Summit participant and geologist Jeff Ryan has maintained longstanding collaborative relationships with faculty members at Western Carolina University (WCU)—a PUI in rural western NC—and, more recently, with Grand Valley State University (GVSU) in Allendale, MI, when one of his WCU collaborators moved to take a position there. This collaboration, formally initiated at a national professional meeting in the mid-1990's, had its roots partly in Ryan's own academic history (he graduated from WCU in 1983 and has maintained an active research interest in the geologic issues of the region). The "fruits" of the collaboration have included a five-year, NSF-funded Research Experiences for Undergraduates summer research program, which focuses on the geology of the southwestern Blue Ridge, in the university's service area. This work has spawned a half-dozen journal publications, as well as joint field courses, faculty/student research visits between the collaborating institutions during the academic year, and the planning and facilitation of instructional field trips for geoscience professionals (including the writing of in-depth geology field-trip guides).

The functional relationship between collaborators has been predicated on complementary resources, as well as shared scientific and educational interests. WCU functions as a “field station” available to Ryan and his students at the University of South Florida (USF), and Ryan’s USF analytical laboratories are available to WCU faculty and students. Ryan’s graduate students at USF (primarily Master’s-level students) have served as “near peer” mentors to participating undergraduates on both campuses, and WCU faculty members have served on USF graduate thesis committees. The move of one collaborator to a second PUI institution did not end the collaborative arrangement, but it did create significant complications in the funding model for ongoing efforts. Three-institution logistics for an REU site became financially untenable in the context of available NSF-REU Program support from the foundation’s Earth Sciences Division. Current efforts at funding joint work have moved toward RUI proposals (based either at WCU or GVSU, with USF as a sub-awardee) or via NSF educational funding (Ryan has an active NSF Course, Curriculum and Laboratory Improvement Program grant, which supports laboratory-based student research efforts on samples collected in the field areas near WCU.

The greatest challenges to continuing the collaboration have been maintaining regular communication and time for research, and the fact that the “orbits” and professional trajectories of PUI and R-1 faculty members are often very different. As an example, Ryan’s recent involvement in the NSF-MARGINS program—an NSF-Ocean Sciences initiative aligned with another of his primary research directions—over the last several years has consumed unusual amounts of time (especially, valuable summer field time) that would otherwise have been devoted to collaborative Blue Ridge research with his WCU and GVSU colleagues. Conversely, the heavy involvement of PUI faculty members in teaching and service on their campuses during the academic year can slow progress on papers, proposals, and research outcomes, which R-1 faculty members may be ill able to afford.

As research productivity constitutes a significant portion of R-1 faculty members’ annual evaluations and tenure/promotion packages, it is important to them that research products (papers, proposals, presentations, etc.) be completed in a reasonably timely manner. In contrast, the demands of PUI faculty members’ jobs differ from those of R-1 colleagues. Measures of “research productivity” at a PUI may be more strongly biased toward research with students, and away from metrics like numbers of publications or successful grant requests, which is seldom the case at an R-1 institution. As well, the weight given to research productivity in the overall evaluation of job performance is likely to be much higher for an R-1 collaborator than for PUI colleagues, who are generally evaluated much more rigorously on their quality of teaching. Honest discussions about what each collaborator needs from the collaboration in terms of productivity will help identify reasonable common objectives and better ways to synergize the skills, resources, and time available for both sides.

Collaborations with Government Agencies and Private-Sector Organizations

Collaborations between PUI faculty members and governmental research agencies are similar to the collaborations faculty at research-intensive institutions undertake, except that differences in job description, day-to-day activities, and the drivers of research productivity are potentially more profound. In many cases, these collaborations involve faculty members' access to a tool or set of tools only available at a government laboratory (examples include the Synchrotron X-Ray Light Source facility at Brookhaven National Laboratories, which is utilized by a wide range of researchers; or the Space Telescope Science Institute, which manages access to observations using the Hubble Space Telescope). A potential challenge peculiar to this kind of collaboration is that access to laboratory facilities and resources may be limited to the faculty member, preventing extensive student involvement. Eleven of twenty-four participants at CUR's Transformative Research Summit have done work at national laboratories or at similar governmental research agencies.

Collaborative partnerships with individuals or organizations in the private-sector appear to be less common (only seven summit participants had had such experiences) and to be more restricted to certain disciplines (for example, computer sciences and biosciences/pharmacology). In the case of a collaboration with an individual, such as a physician running her own practice and research laboratory, the continuation of the collaboration depends heavily on the existence of steady funding. Such funding can come either from government agencies or from commercial investors. In such collaborations, government funding can be crucial to the continuation of fundamental research, since commercial funding is often constrained by sponsor goals such as profitability. Issues of access may be similar to those encountered in governmental laboratories, but an issue unique to private-sector collaborations involves proprietary information—in some cases, even the names of the partnering organizations are privileged. The infrastructure to support research in the private sector may be substantial, but the interests and needs of private-sector collaborators are necessarily constrained by corporate interests. However, a company's desire for successful public relations and outreach may lead to a very welcoming relationship for academic researchers, with the added benefit of possible future employment opportunities for student participants.

International Collaborations

Given the global nature of scholarship generally, and scientific scholarship in particular, it is becoming more and more important to develop and maintain international research connections. Over half of the CUR summit's participants listed some sort of international research collaboration in their overall portfolio of scholarly activities. Such activities typically develop at professional meetings with a strong international component, or they may become established through participation in an international research initiative (examples include the Integrated Ocean Drilling Program and the International Space Station's research efforts in the U.S., Canada, and Europe). Funding agencies may provide support, including through NSF's Office of International Science and Education (OISE) or via Fulbright Research Fellowships. Such support can seed and expand international collaborations by allowing meetings with international research partners and extended research visits. The NSF lists the development of international research partnerships as a very desirable "Broader Impact" category in grant requests and will support international collaborations through standard research grants and through RUI requests paired with grant requests made to European and other foreign granting agencies by international collaborators. Further, NSF has funded "international" REU Site research projects through partnerships between its various directorates or the Office of Polar Programs, and OISE.

The ability to maintain regular, high-quality communication with foreign collaborators is heavily constrained by distance and time differences, but the advent of low cost or no cost E-business and networking resources (email and the Internet; Skype online telephony and conferencing; and social-networking frameworks that can be customized to the needs of participants, such as those available through Google, Wikia and Ning) has made rich, real-time, and asynchronous communication much more feasible and available. Summit participant Jeff Ryan maintains routine contact with international collaborators by using email to schedule Skype Web telephone conversations and to transmit documents, as well as using social-networking tools (blogs and discussion boards) to engage with both foreign and distant U.S. collaborators both live and in an asynchronous manner. Other potentially more-challenging obstacles to mutually effective collaboration include institutional barriers, differing academic/scholarly reward systems and duties, and (at times) markedly different perspectives on education and the involvement of student researchers.

Collaborations with Students

The most common and most available collaborative research relationships for college and university faculty members are those with their research students, be they graduate students at larger universities or undergraduates at PUI's. Collaborative relationships with students, especially undergraduates, are fundamentally different from those with colleagues of any stripe in that research students are in every important way apprentices to their faculty supervisors—they are, by definition, the junior partners in the collaborative relationship. The contributions of undergraduates to collaborations with their research mentors are primarily energy and time, and they can in many cases provide a valuable connection to disciplinary fundamentals in collaborative investigations, as they use the collaboration to learn the methods and content of their disciplines. The challenge for PUI faculty (and, in fact, faculty at any institution where teaching undergraduates is a priority) is to shift the mentor-student relationship to one of true scholarly collaboration.

For faculty members, an element critical to the initiation and success of true research collaborations with their students is instruction that prepares students to conduct research. This necessarily extends beyond a faculty member's own courses to include the entire curriculum, although it is very important that one's own courses provide students with critical research skills, and that they instill in students an investigative mindset (e.g., White, 2007; Tewksbury and MacDonald, 2007; Smith, 2007). The Integrated Laboratory Network at Western Washington University, an NSF-supported effort, seeks to expose students to the research application of cutting-edge analytical tools early in their academic careers (Cancilla and Albon, 2005), while other projects have built extended laboratory activities or term projects around the in-depth use of research instrumentation, (i.e., Beane 2004; Ryan and Beck, 2009).

The establishment of a "research mindset" can be initiated in one faculty member's course, but it must also be supported in other courses through project-based learning activities, the utilization of educational resources that interpretively utilize cutting-edge research results, or authentic structured research exercises (Argast and Tennis, 2004; Epstein et al., 2007; Wagner et al 2007; Ryan and Beck, 2009; Goodwillie et al 2009). The Science Education Resource Center at Carleton College (http://serc.carleton.edu) provides an extensive archive of instructional resources for the conduct of problem-based learning, the use of research data in the classroom, and other investigative pedagogies. The National STEM Digital Library (www.nsdl.org) offers a range of disciplinary and interdisciplinary pathways to Web-based resources that can be used to bring an investigative mindset into college courses at any curricular level.

Equally important is the availability of time within a curriculum for students to do research, as blocks of ostensibly unstructured "research time" can be difficult to carve out of an undergraduate's typical week of coursework. Several chapters in the CUR monograph *Developing and Sustaining a Research-Supportive Curriculum: A Compendium of Successful Practices* (Karukstis and Elgren, eds., 2007) focus on building research time into disciplinary curricula, with focused case-study articles on geoscience, engineering, biology, neuroscience, and psychology. As with collaborations of other stripes, the time to do research with students needs to be explicitly scheduled into the day, both for the logistical reasons noted above and for instructional reasons, because students need to see that their mentors give research time priority.

Concluding Comments

Establishing and nurturing research collaborations are essential elements in any research faculty member's success, and they are critical to generating the intellectual ferment necessary to conduct cutting-edge research in any discipline. For "transformative" research to occur on PUI campuses, particular attention needs to be given both to the development of faculty collaborative links off campus (to other institutions, laboratories, and, as appropriate, private-sector organizations), and to essential on-campus links by fostering true collaborative research activities with students and with faculty members in other departments, where feasible. Models for inter-institutional cooperation, such as the Five Colleges in Amherst, Massachusetts, the Claremont Colleges in California, and the Keck Consortium institutions, potentially offer opportunities for research collaborations that may bear more fruit (in terms of grants and potentially transformative discoveries) than the sum of their parts might indicate. However, to truly "seed the field" for transformative research, it is necessary for individual institutions and groups of institutions to plan for, invest in, and actively sustain a fertile research environment.

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Creating Future Science: The Role of Private Foundations in Shaping Research Activities at PUIs

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Among the many challenges American science faces these days is a scarcity of research funds (public and private) at the very time the nation urgently needs a well-trained workforce to help it maintain a leading role in research, as other nations rapidly develop their scientific and technological infrastructures. Also today, perhaps more than ever, major scientific challenges are deeply intertwined with societal needs. Yet because of our past research successes, today's scientific challenges are increasingly complex, and thus require the combined efforts of scientists from different fields and the use of truly interdisciplinary approaches.

For example, solar energy conversion—vitally important to a global economy potentially facing "peak oil" shortages—is now being tackled by communities of chemists, physicists, materials scientists, and engineers, among others, who are pursuing the same goals but using different concepts and tools. In coming together over the pinch points blocking greater efficiencies in solar conversion, these communities are nurturing intellectual flexibility and, potentially, new hybrid disciplines with their own technical terminologies and new ways of looking at seemingly intractable problems.

A number of top educational institutions are making good progress at encouraging these communities of interest among scientists. For example, the University of Arizona has created the BIO5 Institute to take advantage of the power of the genetic paradigm to encourage cross-fertilization among researchers in biology, medicine, pharmacy, agriculture, basic science, and engineering. And the small, private foundation for which I work, Research Corporation for Science Advancement (RCSA), is getting into the boundary-crossing game with a new program called Scialog, derived from the words "science" and "dialog." Scialog brings together early-career researchers from multiple disciplines and encourages the formation of investigative teams to look at major problems under the general heading of global climate change. RCSA President James Gentile calls the program "an experiment in developing new communities of inquiry for 21st-century science."

Of course, cross-disciplinary communities are not new in the history of science, as is demonstrated by the existence of molecular biology, biochemistry, and materials science. What is new, it seems, is the sense of urgency that comes with the realization that we are facing a broad set of difficult problems on this finite planet with its burgeoning human population. This sense of urgency has given rise to calls for scientific research that is much more deliberately "transformative" in its goals.

What does that mean, precisely? According to a 2007 National Science Board report:

> *Transformative research is defined as research driven by ideas that have the potential to radically change our understanding of an important existing scientific or engineering concept or leading to the creation of a new paradigm or field of science or engineering. Such research also is characterized by its challenge to current understanding or its pathway to new frontiers.*

Or, as the American Academy of Arts and Sciences (AAA&S) defines it, transformative research has "the potential to generate deep changes in concepts, to produce new tools or instrumentation that will allow the entire community to extend its reach, to create a new subfield, or to bring together different fields to make discoveries that would otherwise be impossible." (Advancing Research in Science and Engineering, AAA&S, 2008)

What these two definitions lack is a phrase or two emphasizing the necessity of risk in transformative research. As quoted in the AAA&S "ARISE" report cited above, Albert Einstein said it best: "If at first the idea is not absurd, then there is no hope for it." Funding truly transformative research means taking risks and learning to live with a higher percentage of "failed" experiments. Of course, no well-designed experiment is a failure, because researchers learn new science even when the results don't turn out as hypothesized. Even federal funding agencies, traditionally criticized by some in the research community as being too conservative in doling out tax dollars, are warming to the idea of taking on more risk, as evidenced by the creation of programs such as the NIH Pioneer Award and the NSF Transformative Research Initiative, among others.

Why is RCSA determined that America's PUIs must be positioned to become a global wellspring of transformative science? It is an urgent matter of national security and prosperity in an era when other nations are rapidly improving their scientific and technological infrastructures. The AAA&S's 2008 report puts it well:

We strongly believe that, regardless of overall federal research funding levels, America must invest in young scientists and transformative research in order to sustain its ability to compete in the new global environment.

The PUI Context

PUI faculty members may, in fact, potentially have more flexibility than their colleagues at research universities to conduct high-risk research that may lead to breakthrough discoveries. This is due to an institutional culture that emphasizes both teaching and research activities and where faculty success is not usually tightly connected with a principal investigator's ability to secure large federal grants.

In many cases, however, PUI faculty members have not yet left the traditional comfort zone of working individually in well-defined disciplines, a move that is increasingly seen as necessary to achieve one's full potential. Although support of cutting-edge research in interdisciplinary fields has been identified as a major priority by prominent groups and committees (Facilitating Interdisciplinary Research, The National Academies, 2004), there is still department-level resistance and a notorious lack of funding opportunities for academic scientists who want to conduct this type of research.

It is fair to say that PUI science faculty members have relied largely on private foundations to establish, grow, and sustain their research. For example, in the last decade alone, RCSA through its 50-year-old Cottrell College Science Award (CCSA) program, has helped early-career faculty at hundreds of PUIs develop research programs. Thus, the current situation presents an excellent opportunity for progressively minded, non-risk-averse foundations to further shape the future of science by challenging bright scientists to conduct potentially transformative, interdisciplinary research. By taking this approach, RCSA is also helping PUI undergraduate research move to the next level of excellence.

RCSA's focus on early-career researchers is a longstanding tradition, but it is a need that still demands our attention. As the ARISE report observes:

> *Today's early career faculty will be responsible for our country's future science and technology discoveries and for the education of our future Ph.D.-level scientists and engineers. Yet they face greater obstacles than their more senior colleagues in securing research grants to inaugurate what should be one of the most productive stages in their careers.*

Although the CCSA program continues to be successful, RCSA feels that because America's leadership in scientific research is increasingly challenged by rising knowledge and talent abroad, it is imperative to change the way research is conducted and planned at PUIs.

Instead of funding a wide range of individually formulated projects, the foundation, through an offshoot of the CCSA program called Multi Investigator CCSA (MI-CCSA), intends to challenge the PUI community to engage in more high-risk, potentially high-yield research activities. Federal agencies such as the NSF and NIH have invested large sums to make this happen in our nation's research universities. But what about the PUIs? Are they embracing the cross-disciplinary, team-based teacher/scholar model? Perhaps not so much.

In the MI-CCSA model, faculty members are encouraged to form teams driven by the power of new technologies, our growing understanding of the inherent complexity of nature, and the resulting desire to explore complex problems that are not confined to a single discipline. Obviously, this approach necessitates partnering with faculty members from different departments and disciplines to take advantage of in-house resources.

While RCSA sees its mission of advancing science, in part, as aiding in the creation of widespread new communities of knowledge, the foundation believes that in order to build a national institutional-research culture that embraces cross-disciplinary, frontier research, it is also important to lay the foundations for these communities by establishing in-house collaborations that will impact both research and teaching activities. That is what the MI-CCSA program is intended to do. RCSA believes a solid commitment to interdisciplinary research conducted within a given PUI will do much to advance science and improve twenty-first century science education.

Adjusting Policies and Practices

The National Academies issued a 2004 report, Facilitating Interdisciplinary Research, that called for academic institutions to develop and strengthen existing policies and practices that lower or remove barriers to interdisciplinary work. The report also recommended that institutions make appropriate use of lessons learned from the interdisciplinary work performed in industrial and national laboratories.

Along those lines, for decades RCSA has worked closely with the scientific community and encouraged senior faculty members to support beginning researchers in all aspects of career development, from grant and contract writing to dealing with undergraduates and administrators. AAA&S takes that further, calling for increasing the profile of good mentors with awards and other forms of recognition, saying "Effective mentoring will result in more successful hiring of top candidates, and enhance the reputations of departments and institutions."

As shown in a number of surveys, PUI faculty members usually identify lack of infrastructure, lack of time, and lack of an institutional reward system as the most common barriers to conducting undergraduate research at their institutions (K.K.Karukstis *et al.*, 2009). Thus it is incumbent upon administrations at PUIs to make sure that adequate instrumentation is up and running, facilities are designed for maximum interaction among disciplines, and, most importantly, collaborating faculty members are supported by a structure that increases emphasis on scholarship rather than simply looking to teaching as the most important part of a promotion and tenure process. In order to keep faculty members motivated to conduct cutting-edge research, institutions will need to rethink the way they assess faculty members' success, especially promotion and tenure policies for early-career faculty.

Personnel systems and criteria should reward quality over quantity in evaluating publications; scientist-scholars should be encouraged to become part of multi-investigator initiatives, and, when needed, to team-teach courses without being penalized for not showing individual professional activities. This type of model calls for a looser institutional structure without the traditional departmental boundaries, as well as open communication lines within science divisions and among college administrators. Faculty members need to feel challenged and supported by their administrators! RCSA firmly believes this type of synergy usually leads to solid research programs.

Creating an in-house, highly collaborative research culture also requires that deans and chairs think strategically about new faculty hires. What skills will a new hire bring that complement the existing research environment? What areas of research are necessary to adapt existing research and teaching activities to modern science?

How does RCSA benefit by funding new approaches? First, it is essential to the foundation's overall mission of advancing science to assist researchers in making great discoveries by supporting frontier, high-risk research. Because private foundations usually award smaller dollar amounts than federal agencies, their grant programs are ideal for providing seed money to explore new ideas for which no results have yet been achieved—research often best tackled by early-career faculty. This type of funding is attractive to early-career scientists by giving them the opportunity to think outside the usual paradigms, not a trivial advantage in today's era of generally conservative federal funding decisions.

By asking highly qualified PI's to think creatively and take risks, we are investing our funds in research projects with potentially high payoffs, studies with a decent likelihood of generating high-quality, publishable results. At the very least, the foundation hopes to avoid the conservative thinking often present in federal agencies and during peer review that discourages faculty members from taking risks. "Don't put it in your grant unless you know it will work" too often guides both early-career and established researchers, as the ARISE report and others have noted.

Will the RCSA approach transform science? Sometimes. But even if it doesn't, a project that deliberately seeks to be transformative may be the start of a creative and productive long-term program, demonstrating to federal agencies that relevant research can be conducted at the PUI level and giving faculty members funding opportunities that are typically available mostly to the top research institutions. With today's anticipated scarcity of research funds, it becomes increasingly important to show that PUIs are up to the task of conducting significant research and that their faculty members are active participants in topics associated with science's grand challenges. As a small, private foundation, RCSA can provide resources to start these projects; the ability of our awardees to attract subsequent funding is a measure of the success of our programs.

Teaching Science

By doing this, RCSA is helping to shape the future of science, and it is enabling faculty members and administrators to engage in building new communities of knowledge. Part of that building process fundamentally involves nurturing the use of interdisciplinary approaches in science teaching as well. In addition to providing needed research funds, the CCSA program has been instrumental in helping faculty members promote the teacher/scholar model among college administrators, trustees, and state legislators.

By supporting interdisciplinary and transformative research within the teacher/scholar model prevalent at PUIs, RCSA believes it is helping to improve the way science is taught. The foundation traditionally has maintained that better scholars are also better teachers: They are better informed about the cutting-edge issues of their science, and they are generally more enthusiastic and thus better able to engage undergraduates in hands-on activities in their research projects and in the classroom.

This approach fits nicely with the foundation's long-time commitment to building active undergraduate research communities through faculty development and student involvement. Participating undergraduates benefit hugely from these types of activities by experiencing first-hand how it feels to think like a scientist up against a real problem, rather than merely thinking about science or about the next science exam. It puts eager undergraduates in a strong position to identify great science as a target for their future graduate work.

As the AAA&S has noted:

> *The nation needs to do a better job of attracting "the best and the brightest" to embark on careers as science and engineering faculty. Young scientists are needed for two reasons: (1) to ensure a sufficient number of U.S. researchers for the future, and (2) to increase the chances for fresh, path-breaking ideas and transforming approaches to meeting twenty-first-century challenges to our economic vitality, environment, security, health care system, and way of life. (ARISE, 2008)*

The foundation benefits in this process because high-risk, potentially transformative, interdisciplinary research with undergraduate participation is an aggressive way to create a well-educated workforce that is prepared to tackle challenging projects and increasingly complex problems that require a set of diverse skills. It is the very essence of long-term scientific advancement.

RCSA is not alone in its desire to see undergraduate research across disciplines. In May 2008, a consortium led by the National Science Foundation issued recommendations for, among other things, advancing interdisciplinary research and the curricula associated with it at our nation's colleges and universities. The NSF recommended developing short-, intermediate- and long-term measures of the success of interdisciplinary undergraduate research, as well as increasing the numbers of grants supporting interdisciplinary research and training clusters (IGERT, 2008).

The last two decades have seen such a dramatic expansion of undergraduate research activities at PUIs, both inside and outside the science departments, that now nearly all PUIs have active summer programs and promote undergraduate research as a highly efficient way of teaching and learning (Wedin, 2006). In addition, team-teaching has become a common practice in universities and colleges, allowing students to learn to tackle a problem from different points of view, even when the instructors come from scientific disciplines within the same boundaries. In the transformational model proposed here, undergraduates, both in summer programs and during the academic year, would benefit enormously from being mentored by faculty members with different educational backgrounds. Research universities already use this model, as evidenced by the widespread presence of interdisciplinary centers and institutes.

In the end, all parts of America's scientific infrastructure will benefit from the synergy of collaborative faculty/student projects, both in research and in education. But if this new mix of interdisciplinary, transformative research and the corresponding undergraduate programs is to be successful, administrators and faculty members must be on the same page and commit resources to the enterprise. Historically, the foundation has invested resources in institutional, faculty, and student development; RCSA's commitment to support PUI faculty will continue as long as the PUI community shows the same level of commitment.

TRANSFORMATIVE RESEARCH AT A GLANCE

Research Corporation for Science Advancement(RCSA) sponsors transformative research at primarily undergraduate institutions to:

- Challenge institutions to move to "the next level"
- Foster the best possible teacher-scholars
- Encourage creative thinking
- Encourage risk-taking
- Foster interdisciplinary collaborations and dialogue
- Expose the next generation of scientists to the best modern science
- Prepare our future scientific workforce

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Non-traditional Sources of Research Funding at Predominantly Undergraduate Institutions

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One of the lessons of Economics 101 is the importance of diversifing one's financial portfolio. There are also benefits to diversification of the sources that support a research program. While the majority of research at predominantly undergraduate institutions is funded through the traditional routes of individual research grants from the federal government and national and private foundations, there are alternative sources of funding that can either provide the opportunity to leverage traditional funding or provide the bulk of support for a research program. Those alternative sources of funding include support from industry, state and regional research funding, and subcontracts to federal grants awarded to larger institutions. The nature of the funding ranges from contract funding in which the faculty member promises to deliver a specific product to funds that are intended as broad support for a research program.

The following vignettes, based on interviews with several researchers, illustrate the diversity of funding situations. While there is great variety in the details, there are common themes both in how to seek the funding and the expectations of the funding "agency." The use of non-traditional sources of funding is not appropriate for every research program, however, and some cautions will also be discussed.

Industrial Funding I

The research program of John Gupton, now a professor of chemistry at the University of Richmond, on the chemistry of heterocyclic compounds is an example of this approach. As is true for many projects supported by funding from industry, John Gupton's support began with an individual contact. Prior to joining the faculty at the University of Central Florida, John worked in the agricultural division of Ciba-Geigy, where he developed an understanding of the culture of industrial chemistry. He met a scientist in the agricultural division of Dow Chemical at a seminar at the University of Central Florida which resulted in a collaboration supported by Dow with Gupton and John Idoux, who was then in the chemistry department at the University of Central Florida, and a UCF biochemist. They agreed to prepare compounds of interest to the agricultural division of Dow Chemical and to screen them through a UCF bioassay system and also the Dow bioassay system. Companies often are interested in what could be termed secondary or tertiary projects, which are not part of their core business but are tangentially related; most companies do not have enough internal people to work on these projects so they can be ideal for outsourcing to academe. This is cost effective because the companies don't have to pay fringe benefits to those conducting the projects, and no workers must be laid off when the project is completed. In this particular project, the UCF personnel could publish their research if they didn't disclose the bioassay results of the compounds they were making. Since Gupton's research includes the development of different approaches to preparing types of molecules (synthetic methodology), he and his colleagues on this project were able to identify material that was appropriate for publication. While the researchers showed drafts of the papers to representatives of the company, there was no attempt by the company to dictate the content of the papers.

A second project grew from departmental support from Monsanto to the Chemistry Department at UCF. A former student of John Idoux working at Monsanto had been convinced by his research experience as an undergraduate that an open-ended grant to support undergraduate research would be a good investment. He persuaded Monsanto to provide a grant of $15,000 to $20,000 per year for five years. The publications from that research acknowledged Monsanto's support and included Monsanto co-authors.

A third project, with American Cyanamid, supported a student on contract work to make heterocyclic compounds that had previously been reported in the literature. While much of the chemistry wasn't publishable, the wages provided by the company were larger than an academic stipend, which allowed the master's-level student to work part-time on the contract work and spend the rest of the time on his thesis research. A fourth project, from Ciba-Geigy, also was open-ended, asking only that the Gupton research program at UCF synthesize heterocyclic compounds known as pyrroles.

In discussing these examples, Gupton emphasized that the projects were developed through personal contacts. Alumni can provide those personal contacts, but departmental seminars are a particularly effective way of making them. A seminar that brings in a visitor from industry for an afternoon or an entire day exposes students to a career path with which they may not be familiar. The visit also allows faculty members an opportunity to discuss their research with the visitor in the hopes that they may find common ground. In discussing possible collaborations, faculty members at undergraduate institutions need to make the case that the economies of research in a PUI are balanced by the slower rate of research progress.

Industrial support has provided great flexibility for Gupton's research program, but he emphasizes the importance of delivering what is promised, particularly in contract research. He advises not overreaching in terms of faculty members' abilities, time, or resources. Faculty members also need to be flexible in setting scientific goals for their own research in order to be able to match their capabilities with the needs of industry. For this reason, industry-supported research may not be appropriate for faculty members early in their careers when they are trying to establish a research area. Each faculty member must decide if funding from a company will help advance the research program or will be a distraction.

Industrial Funding II

Support of the biomedical research program of Julio Ramirez, professor of psychology at Davidson College, on the response of the brain to injury is a second example. The overarching focus of Ramirez' research is the brain's ability to reorganize itself after an injury, that is, its neuroplasticity. The area of the brain that he studies, the hippocampal formation, is implicated in Alzheimer's disease, so there is natural interest by drug companies in the research.

His work's industrial connection began in 1996 at a meeting of the Society for Neuroscience when he noticed a poster by a company called Neotherapeutics describing a compound that might be evaluated by the methods used in his research. He asked if the company would be willing to send him a sample of the compound to test. At the next annual meeting of the society, he and company representatives discussed the results. The company was very enthusiastic and initiated a contract with Davidson College that was relatively small at first, $50,000, but was increased to $100,000 as Ramirez included behavioral studies, and then to $200,000 when the studies were expanded to include extensive anatomical research. Ramirez had complete control of the intellectual design of the studies and was able to present and publish the results of the research without restriction.

He continues to have industrial collaborations that broadly fall into two types of arrangements. Some funding, such as that from Neotherapeutics, is considered a research grant. Once the grant is secured, no approval is needed for how the money is spent; there is no oversight and there are no restrictions on publications, as long as the project is executed as the grant outlines. The other type of funding is contract work, for which a fee is paid for the research done. In this situation, the investigator has no intellectual right to the results of the research. An example would be a contract with a company to look at the effects of drugs on brain structure and function, with no intent to publish the scientific work. Rameriz emphasizes that even such "fee-for-service" work has value for undergraduates. It is a bona fide research experience for the students and allows them to hone their research skills. In addition, because the student wages for "fee-for-service" work are often paid at a higher rate than the normal stipend for undergraduate research, some students can more easily afford to be part of the academic research program because they can work fewer hours on the contract work for the same pay as an academic researcher.

It is crucial that the researcher and the company arrive at a clear understanding of the ownership of the intellectual property that results from the research and that there be an unambiguous set of guidelines for the nature of their relationship. A number of institutions have developed procedures for handling contracts, as the section below on "institutional issues" discusses.

Research supported by industrial funding must have an application of interest to the company, so the academic researcher needs to be flexible in his/her research trajectory in this type of arrangement. For this reason, Ramirez says, pre-tenure faculty members should normally be steered away from these sorts of relationships if the possibility of publishing their research is contractually restricted in any way, such as requiring the company's approval for publication. Although it is certainly possible for a research program to emphasize both fundamental and applied research, the applied component may be valued less during promotion and annual salary reviews in the academic setting.

As in other scientific work, a collaboration between a scientist in the academy and one in industry arises from a relationship, which can develop from discussions during research conferences. A cold call to a potential collaborator in industry may be less successful than initiating contact at a meeting where shared interests can be readily explored. As Ramirez says, "Successful collaboration is fundamentally based on a sound relationship."

Industrial Funding III

A third example of industrial support for undergraduate research is research in the chemistry department at Furman University that was initiated by Professor Lon Knight. Whereas the previous vignettes have focused on the collaborations of individual researchers with industry, Knight's work presents a compelling picture of the value of industrial support to an entire department. The department hosts corporate luncheons to interest companies in the possibility of supporting work in the department. He described a recent one in which CEOs of 28 local and regional companies had lunch with 66 students involved in the Furman summer research program. The students were assigned to tables with specific industrial sponsors, with the intent of intellectual cross-fertilization. The CEO or other high-ranking official of the company was given one minute to describe to the entire group the focus of his or her company's commercial effort. During the course of the luncheon, the students had an opportunity to informally discuss their particular research projects. Then four preselected students had 90 seconds to give a synopsis of their research to the group. Knight explained the compressed timeframes, saying "You have to move this along. These are busy people and they need value for their time." The luncheon included a limited number of research posters as icebreakers for students and the industrial representatives; the latter also had the chance to tour the department.

During the luncheon, Knight thanked the industrial representatives for their support—which amounts to over $80,000 per year—telling them, "We couldn't do it without your support." He said that the industrial officials look around at their competitors and wonder who is giving this support and whether their companies should be doing more? What Knight describes is an excellent example of motivational leadership applied to the support of undergraduate research.

The funds from the industrial sponsors contribute to a departmental discretionary fund that is far greater those found at most predominantly undergraduate institutions. The discretionary funds can provide a bridge grant for faculty members who are between traditional grants; money for instrumentation that would allow faculty members to move into a new research area; or other activities that would enhance the departmental research effort.

The industrial contributions started after Knight began talking with the most senior official with whom he could get an appointment at 20 corporations. He painted a picture of undergraduates doing substantive research and mentioned, where appropriate, the Furman alumni who were working for the particular company. He basically said, "You have a great thing in your backyard. Why not support it?" Then he asked each company for a couple of thousand dollars for a student stipend, which was the level when the program started. Support for research has grown to hundreds of thousands of dollars a year, from a variety of sources including federal grants and support from private foundations as well as industrial funding When Knight began these efforts he didn't ask for permission to visit the companies, but he was not seen as a threat to potential gifts by university development or other administrators because he was asking for such small amounts. And the relationships first created with those small gifts make the companies much more responsive to requests from Furman's development staff members because the companies already have a relationship with the institution. This is underscored by the fact that top university administrators—the president, provost, deans, and development representatives—also are invited to the corporate luncheons. A side benefit of the luncheon is the immediate credibility the department achieves when administrators see the high-level industrial representatives who feel it is valuable to attend the luncheons.

The relationship is truly a two-way street. The industrial support has allowed the department to hire an industrial-relations liaison, who can provide free use of departmental instrumentation and access to technicians for the companies who provide research support. There is a small amount of contract work done in the department, usually no more than $6,000 to $8,000 per year. The department has developed credibility with the local and regional companies, which is extremely valuable, so again, it is important that faculty members do not promise more than they can deliver. And because applied research and industrially supported studies are not always given the same weight as fundamental research, either by internal or external reviewers, faculty members in Furman's chemistry department continue to be expected to compete for traditional external research grants and to support their research programs with those grants—maintaining their academic reputation as one of the finest chemistry departments in the country.

Is this model transferrable to other institutions, particularly those that don't have a critical mass of local industries? Knight maintains that proximity is not the crucial element and that a department can effectively solicit industry on a state or region-wide basis, with an argument based on the quality of the research program at the institution. His analogy is a winning football team. Many people have allegiance to a football team located a great distance away from where they live. They support the team not because they grew up with it, but because it is a winning team, with players who are fun to watch because they are so capable. Why wouldn't a company support a department of equally high quality?

When dealing with the companies, Knight stresses demonstrating that researchers are putting the companies' money into quality operations, not through the slick, glossy brochures that development staff are inclined to use, but rather through providing a basic report showing how their money is used and emphasizing that the dollars are going into students and into quality.

Local and Regional Sources of Research Support I

The research program on invasive plants pursued by Kelly Lyons, a biologist at Trinity University, is an example of this. Lyons' research program explores the way that plant diversity and competitive dynamics among plant species can be used to design invasion-resistant plant communities. Her laboratories have typically been the fields of public lands, but in Texas, where most of the land is in private hands, she relies primarily on the good will of local landowners who allow her to use their land to test her theories concerning plant diversity. The landowners' cooperation is absolutely crucial to the success of her research program, but, in the best situations, they become research collaborators. In addition to allowing access to his land, one local landowner mows the grasses of the research area as needed, has helped in the application of prescribed burns to control invasive weeds, and even pays for some of the analyses of plants and soil himself.

Through much trial and error and many rejected proposals, Kelly has developed a knack for finding small pots of money, to supplement other grants, such as one from the U.S. Department of Agriculture. As she designs her research program, she asks what she can do cheaply and designs research projects that will sustain her research program through "thin" times. She has received small grants for soil analyses, but she also collects soil samples and freezes them until she has the money for analysis. She has gotten support from the Native Plant Society of Texas for student research, as well as travel grants from the Ecological Society of America (ESA) and the Consortium of the Americas for Interdisciplinary Science. She emphasizes that the small sums of money are critical to the collection of preliminary data that can bring in the larger sums. For example, the ESA Forrest Shreve Desert Research Grant provided her $2,000 to conduct reconnaissance in the Sonoran Desert. The observations made and data collected during this trip were instrumental in securing funding from the National Science Foundation and the Fulbright Commission to conduct two years of post-doctoral work on this ecosystem.

In pulling together these small pots of research funding, it is often important to become visible. She currently serves on the San Antonio River Extension Environmental Advisory Committee and as a board member of the Friends of Friedrich Park Wilderness Preserve. During her graduate work she served as a tree commissioner for a small town in California. These associations allow her contact with local land managers and public officials and help facilitate a connection between theoretical science and land-management practices.

But critical support for research may not always come in the form of dollars. For example, Lyons volunteered to offer grass-identification workshops at the Cibolo Creek Nature Center in Boerne, Texas. Due to this connection, she is now working with the center and a local landowner to collaborate with well-trained and enthusiastic volunteer "citizen scientists" who will collect publishable data for her and present this data at local and national meetings.

While Lyons has been very successful in identifying sufficient small sums to support her research, she cautions that some grants come with many more strings than others. Thus, she advises researchers to carefully consider the reporting requirements that accompany the funding and, whenever possible, to steer clear of grants that require a lot of reporting. Demanding reporting burdens can make it difficult to find time for the actual science.

The type of science done also affects success in obtaining these types of funding. Lyons' work straddles the fence between theory and application; however, when there are obvious and tangible merits to the work, funding sources—particularly those closely associated with the general public—are more willing to support the research.

State and Regional Funding II

Another type of such support is exemplied by the research program of Anna Cavinato, Professor of Chemistry at Eastern Oregon State University.

Cavinato's training as an analytical chemist emphasized the use of non-destructive analytical methods. When she started her research program at Eastern Oregon, she was working in the area of process analytical chemistry, particularly applications of near-infrared spectroscopy to fermentation processes. But conversations with a colleague from the University of Washington, Barbara Rasco, convinced her that her expertise in non-destructive methods of analysis could be used effectively to solve problems experienced by fisheries, looking first at parameters directly related to chemical analysis, like the salt and moisture content of fish, and then moving to questions like spoilage, which required her to adapt her technique to microbiological assays. At the same time, Cavinato was having conversations on her home campus with scientists from the Oregon Department of Fish and Wildlife, which is housed in the same building as the chemistry department. Those conversations helped her to identify problems that could be solved with non-destructive analytical methods but that also required her to learn new techniques and jargon. The research projects were exceedingly important for the area of Oregon and Washington served by her institution and were of interest to her students because they could see the importance of the work, even though they also required Cavinato to move out of her normal comfort zone in science. Her work has been funded through regional grants from the USDA's Cooperative State Research Educational Extension Service, which were awarded to multiple institutions including Washington State University and then distributed as subcontracts to institutions including Eastern Oregon. They provided funding for students, supplies, and instrumentation. As her expertise became more widely known, Cavinato worked on a subcontract from the University of Alaska to understand the bruising of fish. Her association with the USDA continued in a multi-institutional grant to the Western Regional Agricultural Center. As part of the project she is currently evaluating the production of caviar in live sturgeon using near-infrared (NIR) technology that is capable of penetrating the flesh of the sturgeon without damaging it. She has also received an Oregon Sea grant from the National Oceanic and Atmospheric Association, again to use NIR radiation to study the changes in fish caused by bacterial infections.

The research funding from regional centers or multi-institutional federal grants has been the mainstay of her research program. Eastern Oregon has a new science building with wonderful facilities, but otherwise has very limited resources that would not have allowed her to acquire the instrumentation she needed or provided support for her students on research projects. Her success is due to several factors, the first of which is her willingness to move into new fields and out of her comfort zone. Cavinato said that 10 years ago she would never have imagined that she would be doing fish studies. She also stressed the importance of being willing to work in teams because multidisciplinary research requires expertise in many areas. The importance of a professional network also is important so that a new faculty member has the visibility to make research connections, and, after a researcher is established, the network helps to keep the science current. This is always an issue for faculty at predominantly undergraduate institutions but particularly crucial for faculty members at more isolated institutions. One mechanism for battling the isolation is hosting a seminar series. When faculty members from a research university or industrial scientists visit our campuses, they frequently leave with an elevated sense of the quality of research that we are able to accomplish with our students, as well as having had the opportunity to identify promisng students. With this may also come a greater sense of the viability of collaboration, including providing access to facilities and instrumentation.

Local and Regional Sources of Research Support III

The research program of Michael E. Dorcas, a biologist at Davidson College, on the amphibians and reptiles of North Carolina provides another example. Dorcas' herpetology laboratory conducts a wide variety of projects, from monitoring the ability of mud turtles to co-exist with humans on golf courses (whose ponds may represent the only remaining habitat for these turtles), to salamander parasites, to python research in the Everglades. While his research has been supported by NSF, including through a CAREER grant, he and his students have also received support from the North Carolina Herpetological Society, the Duke Energy Foundation, the National Park Service, the North Carolina Wildlife Resources Commission, and the South Carolina Department of Natural Resources.

As has been true for the other researchers profiled, the key to alternative sources of funding is networking, and the key to effective networking is to become active in regional and state organizations that are related to one's research. For Dorcas, this includes the Southeastern Partners of Amphibians and the North Carolina Herpetological Society. A second route is through volunteer activities. His lab coordinates and participates in a variety of outreach programs and events to raise awareness about reptile and amphibian conservation and to engage the local community in citizen-science projects focusing on the conservation of these animals. These activities include the state's Calling Amphibian Survey Program (CASP), a volunteer-based monitoring program administered by the North Carolina Wildlife Resources Commission. CASP coordinates with the North American Amphibian Monitoring Program, which in turn maintains an online database administered by the United States Geological Survey.

Institutional Issues in Use of Non-traditional Sources of Funding

Two recent books, the 2004 *Buying In or Selling Out? The Commercialization of the American Research University,* edited by Donald Stein, and the 2007 *Science for Sale* by Daniel Greenberg, emphasize the negative aspects of contract research on large research universities. The chapter in Stein's book by Derek Bok is particularly effective in articulating these concerns (Bok, 2004). For scientific results to be useful in advancing knowledge, they need to be free of bias. He suggests that the potential commercialization of a research idea or product can create a predisposition toward a certain result in the investigator's mind, and that this is particularly acute in the testing phase. He and others note that a favorable evaluation of the data can also be forced on the investigator by the industrial source of the funding, that unfavorable data can simply be buried, or that the investigator can be discredited. In such circumstances, "The objectivity of university science will suffer in appearance if not in reality," Bok says.

Non-disclosure agreements or agreements that delay publication of data are understandable from an industrial perspective, Bok notes, but antithetical to the progress of science. We depend on scientists freely sharing data, and it appears that in the biomedical area in particular, the big dollars that are involved in developing and testing new drugs and procedures have had a chilling effect on this free exchange of information. Finally, Bok suggests that the work that is likely to most effectively lead to a profitable product may not reflect the work of greatest scientific merit. In the interest of commercialization, industry may prefer to develop a product that is relatively similar to one that currently exists rather than seeking a riskier, but potentially more beneficial, invention.

The concerns that are articulated in these two books are aimed primarily at large research universities that attract significant research support. The research at PUI's is much smaller in scope and cheaper. However, it would be inappropriate to assume that our research is not susceptible to pressure just because it is not accompanied by large grants. We still have aspirations for our careers, tenure/promotion, and professional visibility that can be affected by funding pressures. Bok has several suggestions applicable to all researchers, advising that universities must develop "clear rules and prohibitions that are widely publicized and conscientiously enforced." He recommends that institutions of similar types get together to create suitable limits on profit-making activities so that competition among institutions doesn't erode the moral high ground. Finally, he describes the importance of federal funding that is stable and of sufficient size to support the research enterprise. As sources of funding dry up, institutions are forced to consider a variety of ways to maintain their operations.

We have limited control over federal funding, but we can create agreements at our institutions that support the free exchange of information and the freedom of scientists to determine the research agenda. Those agreements must be clear and comprehensive and recognize the interests of both the college or university and the industrial sponsor. For example, in the area of publication, the agreement might state that College X shall be free to publish and copyright any information, conclusions, or developments resulting from activity under an agreement after providing the sponsor with 30 days to review each publication for patent purposes and to identify any inadvertent disclosure of proprietary information.

Intellectual property such as patents and inventions are of particular concern to an industrial sponsor. An agreement might indicate that the title to any invention conceived or first reduced to practice at the college or university would remain with the institution, but that the sponsor would be informed of the invention in a timely fashion and would have the first option to license the invention, subject to reasonable terms and conditions. Frequently, proprietary information is shared with the academic researcher. The agreement could indicate the understanding that when this information is divulged to the faculty member, it is designated as confidential at the time of disclosure, with the institution agreeing that for a prescribed period of time, the institution will not disclose the information to a third party without the prior written consent of the sponsor.

There are other issues associated with the interaction of academe and industry, and many of them mirror issues associated with faculty consulting. When the faculty members are using college resources, the college has a stake in the research. This is obvious for a chemist working in a college laboratory, but is less obvious when data are processed using college computer facilities or college-owned software. When negotiations begin with a company, it is hard to know how to "price" a job. In fact, the question of what account to charge expenses against can be a challenge when there is no history of these types of interactions. Many of our institutions experienced this type of uncertainty when they first began to obtain federal funding, but at that time there were investigators at PUI's who had developed expertise with federal funding who could provide information. There are fewer PUI's with expertise with industrial contracts at this time, but there are ways of beginning to develop a process on a campus. One contact needs to be with the nearest state university with a technology transfer office so that you understand issues that are specific to your state laws. A campus also can hire expertise from savvy universities to review legal language. For a large contract, the cost of this review may be a very important investment.

There are at least three organizations that can assist with the development of policies that protect both the interests of the researcher and the institution and those of the industrial sponsor. The professional organization to which many grants officers belong is NCURA, the National Council of University Research Administrators. Its Web site includes links to a number of grants offices, and while the majority of members are from major research universities, non-research-intensive public and private campuses also are well represented, including an interesting mix of PUI's. The American Association of State Colleges and Universities (AASCU) has a grants resource center (GRC) that offers a number of services, such as publications that provide assistance with government regulations, information on private-sector grant opportunities, and updates on existing and future program initiatives. Of particular benefit is the GRC ListServ, which can provide quick answers to questions on issues associated with many types of extramural funding. Finally, SRA International, a professional organization created to support and educate research administrators, offers a number of services, including workshops. For example, the 2008 meeting had a workshop for new research administrators that focused on the legal aspects of research administration, starting with intellectual-property issues and continuing through contract and grant matters. The At-Large division of the Council on Undergraduate Research includes many people associated with the sponsored-projects office of their predominantly undergraduate institutions, and I appreciate the comments on this section from Franci Farnsworth of Middlebury College and Melvin Druelinger of Colorado State University-Pueblo.

Summary

Faculty at predominantly undergraduate institutions, as well as those at major research institutions, can benefit from funding from less traditional sources, such as industry and local and state entities. Because industry and academic researchers may have different expectations for the use of the knowledge created by these collaborations, it is crucial that both parties understand the details of publication and other intellectual-property issues. There are a number of organizations, noted above, that can provide guidance in dealing with these issues. Contract work with an industrial sponsor may not be in the best interests of a pre-tenure faculty member because of potential difficulties in publishing the results of the work. In the vast majority of cases, collaborations of the type described in this chapter are the result of personal interactions, so faculty members should be encouraged to attend professional meetings where they can interact with representatives of potential funders; to use departmental seminar series to initiate interactions and to provide information about their institution; and to become involved with professional groups in their local area.

The focus of this chapter has been primarily on the impact of non-traditional sources of research funding on the research program of a faculty member. It is important to remember that our students are also important stakeholders. While non-traditional funding may allow a faculty member to offer a research opportunity to a student that might not exist in the absence of the funding, we should not forget the benefit to the student of publication. Even the local publication of an honors thesis, which would normally end up in the college library, could be compromised by a failure to understand the details of the interactions between researcher and funding source. It is far better to get this process right from the beginning.

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Transformative Research Summit Recommendations

1. The Council on Undergraduate Research (CUR) should use its national voice to call attention to the role of undergraduate institutions, particularly the smaller institutions, in producing scientists who conduct transformative research. CUR should also call attention to the undergraduate students who are engaged in research that is potentially transformative.

2. The Council on Undergraduate Research, institutions, and scientists should consider the "big ideas" or "grand challenges of the future" in developing research agendas and encourage undergraduate students to think about these ideas as they consider their future as researchers.

3. Institutions and faculties should seek ways to reduce and remove barriers and disincentives to engagement in transformative research. Examples include the following: enhancing opportunities for faculty members to talk across disciplines, reducing curricular rigidity for students, creating incentives for writing grant proposals, aiding faculty members in finding collaborators and securing funding for potentially transformative research, and modifying tenure and promotion documents to support faculty members engaged in research that is increasingly collaborative, interdisciplinary, and high-risk.

4. Institutions and faculties should address faculty work load and faculty reward systems to include student mentoring, research/scholarly activity and outcomes, and availability of support staff to provide time for collaborative research with undergraduate students.

5. Funding agencies and foundations should achieve a more diverse representation on review panels, Committees of Visitors, task forces, committees, boards, etc. that includes faculty members from primarily undergraduate institutions.

6. Funding agencies and foundations should include opportunities for faculty at primarily undergraduate institutions to support postdocs and technicians through grant budgets.

7. Funding agencies and foundations should develop more cross-disciplinary programs to encourage the possibility of cross-disciplinary transformative research."

Appendix

Intellectual Property Policy

Adopted by the University, January 2008

Preamble

DePauw University benefits from an active and productive faculty, and from encouraging faculty work and creativity both on and off the Greencastle campus. Intellectual property inevitably will be created in the course of research, teaching and service activities of DePauw University's faculty members and staff members. By longstanding practice, DePauw University has recognized and honored the academic tradition that individual faculty members own the copyrights of course-related, scholarly, and other creative original works of authorship that they produce in the course of their employment by DePauw University. DePauw University continues to recognize and honor this academic tradition, notwithstanding that federal law may give DePauw University presumptive ownership of original works of authorship created by its faculty within the scope of their employment. Accordingly, this DePauw University Intellectual Property Policy (the "Policy") identifies the ownership interests of DePauw University and its faculty members and staff members with respect to original works of authorship created in the academic setting. This Policy is incorporated by reference into the policies governing conditions of employment of all DePauw University employees, and is binding as between DePauw University and its employees. In the event that this Policy, in conjunction with federal copyright or intellectual property law, does not effect the desired rights of ownership described below, DePauw University and its employees shall work in a good faith manner consistent with the principles in this Policy and execute any documentation necessary to carry out the intent of this Policy and its desired results.

Rights of Ownership

I. University Works

DePauw University shall own all "University Works," meaning original works of authorship or invention that are created, in whole or in part:

with the use of "Substantial University Resources," meaning financial, material, personnel or other support provided to an employee that is beyond the level of common research and teaching support typically provided by DePauw University to that employee. [Note: This accounts for, and by implication assumes, that faculty members may be supported at differing levels, i.e. there is not a standard/definable support applicable to all]; or

as a specific requirement of employment, pursuant to an explicit DePauw University assignment by a supervisor or duty, on commission from DePauw University for its own use, or pursuant to a gift, grant or contract which requires ownership by DePauw University.

University Works shall be owned by DePauw University as works made for hire within the scope of employment by DePauw University. The following works presumptively shall be considered University Works: "Courses," meaning the copyrightable videotapes and other recordings of all course lectures, classes, or presentations;

"University Publications," meaning DePauw University-sponsored or owned journals, periodicals, newsletters, yearbooks and other print or electronic publications; and

"University Administrative Materials," meaning policies, curricula, promotional materials, web sites, and similar works, including but not limited to works created for faculty and DePauw University committees, works created by faculty members in assigned administrative roles, and works created by department chairs and program coordinators on behalf of their programs.

DePauw University grants faculty members and staff members non-exclusive rights to noncommercial use and distribution of University Works that they have authored unless otherwise prohibited by contractual or legal restrictions.

II. Staff Works

DePauw University shall own all "Staff Works," meaning original works of authorship that are created:

by non-faculty employees within the scope of employment by DePauw University; or

by non-employees, consultants, or contractors expressly for DePauw University.

Exceptions may be granted in particular circumstances, such as for work done in an approved consultancy for another institution, or creative and scholarly work produced with DePauw University resources not related to the job description if so identified by the supervising vice president. DePauw University does not claim ownership of works created by non-faculty employees outside of the scope of employment by DePauw University.

III. Faculty Works

Faculty members shall own all "Faculty Works," meaning original works of authorship that reflect scholarly research and creativity produced by and on the initiative of faculty members within the scope of their employment by DePauw University, including but not limited to: syllabi for courses, tests, assignments, instructor's notes, instructional materials (including websites and videos), textbooks, monographs, journal articles, other works of non-fiction and fiction, poems, speeches and other creative works such as musical compositions and visual works of art. As an exception, the University Communication Policy governs the right of the University to take possession of or to provide access to materials produced using the University's electronic communications system when required by law or when there is evidence of violation of University policies.

Academic departments, the Committee on Faculty in the course of its deliberations, or the DePauw University administration may require individual faculty members to share copies of scholarly research and creativity, such as instructional and other materials used for ordinary classroom and program use, as part of the ordinary processes of administration, evaluation and internal or external review or in case of a disciplinary hearing. Additionally, faculty members may be asked to provide copies of scholarly research and creativity as part of internal or external review processes or in the course of applying for DePauw University funding of scholarly and other creative work. Such requirements to share and permit limited use of these works shall not otherwise limit a faculty member's copyright in scholarly research and creativity.

In cases where DePauw University is asked to make an extraordinary investment to enable faculty research or other work, ownership conditions will be negotiated at the time of the approval of the request for investment so that DePauw University may receive a fair return on its investment. In the case of scholarly, creative, or pedagogical work done collaboratively with other institutions or for-profit corporations, or where granting bodies take a different approach to ownership, agreements may be worked out ahead of time and subject to review and revision by the Chief Academic Officer, who shall apply the principle of maximizing academic freedom, fair use, open scholarly inquiry, and respect for the rights of authors and inventors.

IV. Student Works

Students shall own all "Student Works," meaning materials produced as part of their academic work for graduation credit, including materials produced for particular courses, such as, written assignments, creative and artistic work, quizzes and examinations. As an exception, the University Communication Policy governs the right of the University to take possession of or to provide access to materials produced using the University's electronic communications system when required by law or when there is evidence of violation of University policies.

Materials produced by students as employees of the University are governed by the "staff works" section of this policy.

Work by students produced in collaborative projects with faculty members or other DePauw employees shall be governed by the policies that govern the University employees unless there are particular stipulations made at the time of the start of the collaborative project.

Student works may be copied and retained by faculty members for use as needed in fulfilling their responsibilities as faculty members (such as verifying authenticity and originality) and as part of the academic personnel evaluation policy. A student work may not be shared by a faculty member with others outside of the previous provisions without permission of the student.

In cases where DePauw University is asked to make an extraordinary investment to enable student research or other work, DePauw University ownership conditions will be negotiated prior to the approval of the investment so that DePauw University may receive a fair return (minimally reimbursement) on its investment. In the case of scholarly, creative, or pedagogical work done collaboratively with other institutions or for-profit corporations, or where external funding agencies take a different approach to ownership, agreements may be worked out ahead of time and are subject to review and revision and final approval by the Chief Academic Officer, who shall apply the principle of maximizing academic freedom, fair use, open scholarly inquiry, and respect for the rights of authors and inventors.

Students who produce work during internships for hosts other than DePauw University (even if for academic credit and if partially supported by stipends from DePauw) shall retain ownership of those products except as they may be required to assign those rights to their internship hosts.

Copyright Notice and Use of the DePauw University Name

I. Notice

The following form of copyright notice shall be used on all University Works or any other works owned by DePauw University:

©[year of first publication] DePauw University. All Rights Reserved.

II. Use of the DePauw University Name

The DePauw University name, associated symbols, and seal are important and valuable representations of DePauw University and its academic reputation. Therefore, use of the DePauw University name, associated symbols, and seal in connection with a work, other than for the sole purpose of identifying the author as a university employee or as a student affiliated with DePauw University, requires the advanced written permission of the supervising DePauw University Vice President. This does not limit the right of university employees or students to use the DePauw University name in accurate descriptions of events and activities that have taken place at DePauw. Furthermore, faculty members, staff members and students at DePauw University may not participate in the creation or use of works that might give the impression of DePauw University sponsorship where there is none. If the DePauw University name, associated symbols, or seal is to be used in connection with any works created under collaborative agreements with outside entities, other than to identify the creator by his or her title at DePauw University, such agreements must be approved in advance and in writing by an authorized DePauw University administrator.

Administration, Interpretation and Dispute Resolution

Interpretation of this Policy

I. Administration

This policy shall be administered by the supervising vice presidents.

II. Interpretation and Dispute Resolution

All issues of interpretation and dispute resolution shall be managed by the Executive Vice President or another senior officer designated by the President.

Transformative Research Summit
Snowbird, Utah
June 10–12, 2009
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