A university without departments and colleges -A new structure to strengthen disciplinary and interdisciplinary education and research

***Solomon Bililign*[1]**
Department of Physics, North Carolina A&T State University, Greensboro, NC 27411, USA
E-mail: Bililign@ncat.edu
Phone: 336-285-2328
Fax: 336- 256-2542
Keith Schimmel
Department of Energy and Environmental Systems, North Carolina A&T State University, NC 27411, USA
E-mail: schimmel@ncat.edu,
Phone: 336-285-2329
Fax: 336-256-2542
J. P. Roop
Department of Mathematics, North Carolina A&T State University, NC 27411, USA
Email: jproop@yahoo.com
Phone: 336-285-2033
Fax: 336-256-0876
Gregory Meyerson
Department of English, North Carolina A&T State University, NC 27411, USA
E-mail: gmeyerson@triad.rr.com
Phone: 336-370-4086
Fax: 336-334-7771

Abstract

A 21st century workforce must be trained to solve not only major national and global challenges but to fit into the current complex work environment. The challenges cannot be solved by a single discipline and require interdisciplinary solutions only possible through the collaboration of physical, biological, and social scientists along with engineers. The 21st century student needs to be educated so they can combine disciplinary depth with the ability to reach out to other disciplines. Such training requires a cost-effective higher education structure that promotes and sustains interdisciplinary research and education (IDRE). The current structure has failed to achieve this. In response to this failure, some private universities like Dartmouth and Olin and public institutions like the University of California Merced (UC Merced) are experimenting with giving up traditional department silos and majors in favor of an interdisciplinary organization. These programs can serve as models for what is to be done in U.S. higher education and may also serve as models for emerging universities in the developing world.

1. Introduction

A 21st century workforce must be trained to solve not only major national and global challenges but to fit into the current complex work environment. Such training requires a flexible, cost-effective higher education structure that promotes and sustains interdisciplinary research and education (IDRE). The current structure serves as a barrier to, and not a platform for, transformational IDRE. Some private universities like Dartmouth and Olin and public institutions like UC Merced and programs like the Energy and Environmental Systems Ph.D. program at North Carolina A&T State University are experimenting with giving up traditional departments in favor of an interdisciplinary organization. These programs can serve as models for what is to be done in higher education.

The U.S. National Academy of Sciences (NAS, 2004) and the 2008 IGERT program directors' workshop made several recommendations to advance IDRE and for developing transformative IDRE (Van Hartesveldt, 2008): (1) allocating resources to interdisciplinary units outside departments or schools; (2) developing central facilities that are at the disposal of faculty members from across campus or even from groups of universities; (3) allocating research space to projects as well as to departments, and allocating a percentage of all projects' indirect costs to supporting IDRE infrastructure; (4) ensuring that any reward system, e.g., promotion or tenure, recognizes both the inherent difficulty and the potential value of IDRE; (5) and creating shared social spaces, e.g. common rooms or seminar series, in which researchers may physically meet in an informal setting; (6) the establishment of new organizational models facilitating open-ended scientific discovery and addressing social challenges; (7) the development of goals and measures of success; and (8) the development of more dynamic and flexible structures with some fluidity of movement and the elimination of hierarchical structures.

Universities' administrative structure is a major barrier to IDRE. Interdisciplinary centers, institutes and degree programs are still dominated by traditional disciplinary culture. In an address to the Ninth Annual Meeting of the Council of Graduate Schools in the U.S. (1969) Daniel Alpert noted that "most universities have established multidisciplinary centers that essentially serve the departments. If the university wants to address itself to today's problems, it must establish interdisciplinary centers which are administered, staffed, and run very differently from those of the present" (Alpert, 1969). Thus, any of the recommended changes fall short of enhancing full-fledged interdisciplinarity. To this day, the narrow academic department still forms the predominant context within which education and research occur**.** Discipline-oriented departments are in charge of teaching, faculty advancement, degree programs and even ownership of courses. Further, university funding processes reinforce this departmental structure. The university structure reinforces the culture in each discipline and increases the communication barrier. The administrative structure undergirds the funding practices that hinder collaboration. Despite the agreement to develop interdisciplinary training of students and attempts to implement the recommendations, the success remains limited. IDRE typically requires that leaders create and sustain an interdisciplinary culture (Derrick, 2012). It necessitates long term vision and planning by the institution irrespective of who is in the leadership positions. Universities need leaders with long term vision who can accept risks and are committed to the cause and willing to establish physical and financial structures that facilitate cross-disciplinary research and education. Ultimately, real success in IDRE is possible only if the effort is initiated and led by faculty.

Serious IDRE requires structured and deliberative initiatives and cannot happen spontaneously. Several authors suggest that such initiatives are necessary to generate a supportive culture and that they can, along with changes in institutional policy, facilitate high levels of success (Amabile et al., 2001; Eagan, Cook, & Joeres, 2002; Lattuca, 2002). IDRE projects should be flexible enough to allow researchers easily to enter and exit short-term collaborations (Rhoten, 2004). Research institutions that fail to address the needs of IDRE will miss research funding opportunities, lag behind in research areas, and may even lose their most innovative and enthusiastic researchers and, thus, fail to be relevant in a fast changing global and interdisciplinary economy.

In this article we will show how the current university structure acts as the major barrier both for the creation and sustaining of interdisciplinary research and education but also for the growth of traditional disciplines. We will show how the overall decline in the levels of achievement and interest in STEM fields in the U.S. and the inadequate supply of skilled STEM workers is linked to this barrier. We will provide data to show the successes of the institutions that are experimenting with giving up traditional department silos and majors in favor of an interdisciplinary organization and how they can be used as models to make higher education institutions to be cost effective in producing the 21st century workforce.

2. Vital Importance of IDRE to Scientific Research and Education

The National Academies state that “Interdisciplinary Research and Education (IDRE) 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” (NAS, 2004). IDRE links and integrates theoretical frameworks and analytical strengths from two or more disparate disciplines and employs methods and skills from them (Aboelela, 2007). IDRE promotes intellectual maturity by providing the differing perspectives of collaborating disciplines and preparing students for the complexity of the real world. IDRE allows for higher level cognitive processing by providing the motivation for deeper learning (Ivanitskaya, Clark, Montgomery, & Primeau, 2002).

The increasing complexity of societal challenges requires sophisticated research tools, concepts and methods from various disciplines. The educational backgrounds needed by those who will meet these challenges cannot be provided by a single discipline. For example, it is not possible to study the Earth’s climate without experts from multiple disciplines. The complexities increase when we attempt to understand disasters linked to climate change, where the interactions between the physical and biological processes intertwine with socio-cultural systems. Such events offer insight into people's perceptions of and relationship to environmental forces (Pfister, 2007). Another example is research in nanoscience, nanotechnology and materials science. Nanotechnology has been compared to the renaissance and is expected to manifest itself in unimagined ways (Fritz, 2002). Other major issues that face society— public health, food/water security, and sustainable development— require a collective effort by interdisciplinary groups.

Policy makers and the public increasingly expect scientific research to result in transformative socio-economic impact. Changes in policy are said to be based on the integration of scientific information with data on the social impacts of the research outcomes and products (Heberlein, 1988). However, IDRE is highly vulnerable to discipline-dominated academic structures (Henry, 2005). In the competition for increasingly scarce resources, interdisciplinary programs are often marginalized or assimilated into mainstream departments without regard to goodness of fit. Though disciplinary specializations have led to great advances, such specializations are no longer sufficient to advance innovation and to address the scientific, technological and societal needs of modern society (Klein, 1996).

3. Intellectual Barriers to IDRE

The intellectual boundaries of today’s research do not always map onto disciplinary frameworks that were developed and organized over centuries. Therefore, federal funding agencies such as the National Institutes of Health (NIH) and the National Science Foundation (NSF) have promoted the blurring of disciplinary boundaries by offering support for research that is explicitly "cross-cutting" or "bridging” between disciplines. Recent efforts to change the review process for interdisciplinary proposals have also helped to overcome investigators’ fear that reviewers using the traditional process for peer review can have trouble evaluating projects that cross disciplinary or program boundaries (AAAS, 2011).

Supporters of IDRE contend that academic institutions hinder scientific advances and limit the contributions of science and technology to society by maintaining traditional single department approaches and organizations associated with disciplinary specializations (NAS, 2004). Any academic’s paradigm is strongly influenced by the home discipline (Giri, 1998; Kumar Giri, 2002). The approaches to promoting interdisciplinary programs have varied. Most of the time, the “new” approach consists of doing more of the same - creating new departments with interdisciplinary labels. At other times, we see calls for total transformation of a university’s structure: wholesale elimination of disciplinary departments in favor of "problem-focused programs" (Taylor, 2009). Both approaches weaken the whole academic enterprise. Removing administrative barriers is not the same as doing away with disciplines. The administrative unit that houses disciplines should be distinguished from the disciplines themselves. Neither relabeling the disciplines nor abolishing them will work.

The main challenge is to enhance interdisciplinary education and research while maintaining strong disciplinary depth under the current academic structure. The current academic structure has been cited as the main barrier to IDRE by most researchers. Funding in universities is linked to disciplinary programs. When institutions are financially strapped, they have a tendency to protect "core" activities such as disciplinary research; this sort of "protection" creates dramatic fluctuations in support for IDRE (Derrick, 2012).

A number of authors have identified a variety of factors that can contribute to failure of IDRE (Brewer, 1999; Caruso, 2001; Feller, 2002; Golde & Gallagher, 1999; NAS, 2004; Pellmar, 2002; Rhoten, 2003; Rhoten & Parker, 2004; Siedlok, 2009; Young, 2000).While we do not yet fully understand all the factors that facilitate IDRE or all the barriers that inhibit IDRE, we summarize some of the main barriers here.

3-a Pride in One's Discipline

Success in interdisciplinary efforts requires expertise in one's discipline, good interpersonal skills, at least one strong leader, commitment, flexibility and willingness to learn and work. The personality traits that appear to matter in interdisciplinary efforts include willingness to accept alternative methodologies, the ability to learn rapidly, good leadership skills and an interest in real world issues that have long term impacts (Jacobs, 2009; Naomi Jacobs, 2010). Amabile et al. (Amabile et al., 2001) defined three characteristics that may impact the success of IDRE: (1) collaborative skills, (2) project relevant skills, and (3) motivation. Additional important elements for collaboration include trust; mutual respect for other members; appreciation, understanding, and respect for other disciplines; and the ability and the willingness to develop a common language based on the realization that the cross fertilization of ideas among disciplines facilitates innovation and creativity.

Nearly all university faculty members are trained in disciplinary programs with specific majors and departmental affiliations. Their values and methods are instilled during graduate school. Disciplinary chauvinism often results with other disciplines viewed as less rigorous or important. This sense of superiority produces a real barrier to equal partnership in the research enterprise between social scientists and STEM professionals (Stepien, 1993).

Researchers may also resist participation in IDRE because of the rigidity of the academic structure. Faculty members insist on staying within disciplines even when conducting IDRE, because they often feel individuals who conduct IDRE are discriminated against by people from outside their self-defined category (the 'in-group') (Fay, Borrill, Amir, Haward, & West, 2006). Feelings of disciplinary superiority will produce distrust between researchers (Groark, 1996) leading to heated (and unproductive) discussions when people with different backgrounds try to assert the correctness of their views (NAS, 2004).

3-b. Barriers to Student Success

To be effective contributors to the economic development of the U.S., students need to learn to communicate effectively across disciplines, cultures and industries (Berry, 2005; Derrick, 2012; Eagan et al., 2002; Gallagher, 1993). While a strong, in-depth background in a discipline is essential for investigating these complex issues, real-life solutions require a 'synthesizing mind' (Gardner, 2006) that can engage in interdisciplinary translation and synthesis, both within multidisciplinary teams and as individuals, with the aim of developing more comprehensive pictures of problems and their possible solutions (Golding, 2009). The implication is that we must educate for both disciplinary and interdisciplinary expertise. Since they will see the common concepts that appear in all disciplines, students who engage in rich cross-disciplinary experiences will have a deeper conceptual understanding of science, mathematics, and social sciences content (Frykholm & Glasson, 2005; Zeidler, 2002), which will improve their grasp of disciplinary concepts (Berry, 2005).

Disciplinary barriers can be burdensome for students conducting IDRE for their thesis or dissertation because these students must meet traditional departmental graduation requirements. Departments have nearly complete control over administering financial support for students, determining the curriculum and setting the standards to meet various requirements (Golde & Gallagher, 1999). Departments own and control courses. The current academic structure has led to excessive redundancy in course offerings, limiting opportunities for students in course selection. Each department offers what it considers its "core-disciplinary courses" with little or no effort to show relevance to other disciplines. The current structure and lack of collaboration between the various academic silos has several consequences in the learning outcomes of students. A structure that allows interdisciplinary course and project opportunities can help students learn the value of thinking in non-traditional ways. It provides faculty members opportunities to work and teach in teams, which in turn allow students to learn 'teaming' skills.

3-c. Problem with Transfer of Knowledge from One Discipline to Another

Transfer is the ability to extend what one has learned in one context to new contexts. If students are unable to transfer what they are learning from course to course or discipline to discipline, they will have difficulty applying what they have learned to solve new problems. Research is lacking on how to help learners transfer competencies learned in one discipline or topic area outside the discipline or topic area (NRC, 2012). Helping students develop transferable knowledge that can be applied to solve new problems or respond effectively to new situations is being hindered by the current disciplinary structure. It is important to provide opportunities for students to use knowledge in multiple contexts so that they can see how skills or problem-solving strategies can be generalized. This approach is again hindered by the lack of collaboration among the disciplines in design and development of courses to meet the needs of the students in a variety of settings. The segregation of disciplines by departments is the reason why faculty lack experience in developing and assessing course offerings that cut across disciplinary boundaries within the traditional STEM communities or those offerings that explore the ethical or socio-economical dimensions of STEM fields.

A finding from the study by Cui (Cui, 2006) is that a majority of STEM students possess requisite calculus skills, yet have difficulties in applying them in the context of physics, being unclear about the criteria to determine whether calculus is applicable in a given problem. This result is consistent with previous research on transfer of learning from algebra to physics (Tuminaro, 2004). Another example of transferability problems occurs when physicists teach physics to biology or pre-med students. (Meredith & Bolker, 2012; Meredith & Redish, 2013) pointed out the lack of biological relevance in traditional physics courses as a problem since the introductory sequence is the only physics that life-sciences students take. Introductory physics does not support students in biology, a field that has grown explosively with the development of new techniques and instruments that enable biologists to gain deeper understanding of the physiochemical processes of life at all scales.

3-d. Lack of Shared Models and Common Language

A related problem to disciplinary compartmentalization is the absence of both shared models and common language, leading to ineffective communication (Adrianna Kezar, 2009; Susan H. Frost, 2003; Wear, 1999). Disciplinary journals or textbooks use different notations or create their own particular vocabularies (jargon) to describe the same thing. One often needs to make the notations and the jargon in other disciplines commensurate with each other to be able to communicate and work effectively on IDRE. It is hard to comprehend disciplinary jargon used, for example, in seminars and published articles (Jeffrey, 2003; Massey et al., 2006). The notations, symbols, and equations used often change even within the sciences. Students taking electives in other disciplines could easily get lost and misunderstand concepts that they have seen previously in the courses in their major area. Researchers undertaking IDRE have reported issues of this nature, where the same word can mean different things in the 'languages' of different disciplines (Bruce, Lyall, Tait, & Williams, 2004). Pickett (Pickett, Burch, & Grove, 1999) note that issues of communication can arise due to differences in context and assumptions. Researchers are often unwilling to move outside a personal perspective or from their own discipline, a view that may have been developed over the course of many years (Gooch, 2005). Many researchers understand the rigidity of disciplinary structures, but they persist in staying well within them and are reluctant to move to an interdisciplinary mode of working.

3-e. Redundancy and Duplication in Course Offerings

The division of university programs by departmental and college silos leads to unnecessary duplication. In universities with diverse academic structures, students' education is actively compromised by duplication. One example is a course in thermodynamics - offered in different forms in physics, chemistry (chemical thermodynamics), engineering (engineering thermodynamics), and meteorology (atmospheric thermodynamics), in which nomenclature and sometimes even sign conventions are different. But it is possible to develop a course in thermodynamics that introduces the basic laws and how they can be applied in the other disciples. In so doing, it is possible to use the same language and notation throughout, avoiding and overcoming the language barrier, and saving the resources used in offering multiple similar courses.

Another example of this phenomenon is in the teaching of statistics and computer programming. A student may take what is in essence the exact same statistics course within the mathematics, economics, biology, agriculture, and nursing departments. The students' transcript will show many statistics courses, but they are only learning the same material repeatedly. In addition, several courses are used to teach computer programming skills. The mathematics, computer science, and engineering departments all offer courses in Matlab, C, or Java, however, because of a lack of institutional oversight, the majority of the time in the courses is devoted to basic syntax and flow control rather than any real disciplinary application of the programming language. To this end, interdisciplinary course offerings are often sloppy and overly elementary.

4. Structural Barriers to IDRE

The dominant structures for research and education within universities make it difficult to conduct IDRE. What was once a single field, natural philosophy, is now fragmented, yet IDRE in science may be considered as old as scientific investigation itself. A problem-based approach has been the main vehicle for scientific investigation since the time of Copernicus. As recently as the late 19th century, disciplines started to define the topics of acceptable research and controlling pedagogy and institutional organization. The university came to be defined as a place of learning through the disciplines (Rogers, 2003). Disciplinary "experts" control content and define which areas of research are worthy of funding and publication. These experts have the power to label outsiders as non-rigorous (Weiner, 1998). Interdisciplinary work is discouraged and often not given the same respect as disciplinary research (Siedlok, 2009); or it is simply viewed as a distraction (Shinn, 2006). Those who pursue interdisciplinary work are often penalized (Leshner, 2004). All this said, (Clark, 1995) actually identified over 8,530 disciplines and fields of knowledge, and many more are being created as research becomes more specialized.

Also, research funding flows into disciplinary units; hiring is done by them, and literally the entire university's physical plant is delineated by the disciplinary division of knowledge. Deans, department chairs, and other administrators are mainly rewarded for strengthening their own departments but not for building links to others. The university today is partitioned along academic lines that suffocate ingenuity, no longer truly reflecting modern intellectual life. Academic units are just categories that help non-academic accountants and business managers to build a budget (Gazzaniga, 1998). The subsequent reward structure aggravates turf wars to the point that often college deans and department chairs brag about how they have successfully negotiated to increase their budget and holdings while forgetting that they are working for the greater good. Often loyalty to a department or college leads to irrational and anti-interdisciplinary decisions in an effort to maintain the status quo. The general interest of the students, university, and greater public is compromised.

Methods and criteria of evaluation are different for different disciplines. It may be difficult for interdisciplinary team members to evaluate each other's performance (Anbar, 1986). Reward systems and practices regarding authorship of refereed publications differ among disciplines and even in different branches within a given discipline (King CR, 1997; MOORE, 1989). Interdisciplinary team members may lack training and proficiency in English communication skills that, in turn, may affect productivity (Barrick, 1998; Cooley, 1994).

Judgment by disciplinary peers determines the reward structure while departmental allegiances guarantee professional recognition. Thus, it is hard to have publications recognized by disciplinary peers when faculty members pursue IDRE (Feller, 2006; Mansilla, Feller, & Gardner, 2006). Evaluation, promotion, and tenure processes often do not properly evaluate collaborative and interdisciplinary work. The culture and climate of departments and campuses are mostly indifferent or sometimes even hostile to such activities (Sa, 2008). Furthermore, the accreditation of degree programs follows strict disciplinary guidelines, and it is even conceivable that a top scientific program could risk losing accreditation over irrelevant and even nonsensical accreditation criteria. While many universities indicate that they wish to encourage IDRE, and some thoroughly describe reforms and place them as strategic priorities, they do not take the necessary steps to adopt the appropriate structures or provide appropriate incentives (or remove disincentives) for faculty members (Rhoten, 2004). For example, some institutions expect faculty to take IDRE-related responsibilities as additional duties beyond their regular duties with the consequence that a change in college leadership could place faculty who do not cover their disciplinary bases in jeopardy of being denied tenure or receiving a negative evaluation.

5. Lessons from Organizational Strategies to Foster IDRE

IDRE is promoted by a number of universities through the establishment of interdepartmental or interdisciplinary degree programs (IDPs) or organized research units (centers and institutes). Several different processes to create and fund organized research units (ORUs) have appeared. Some are created as strategic administrative decisions and are provided seed funding (e.g., Ohio State University, North Carolina State University, Rutgers University, UC Berkeley, University of Connecticut, University of Virginia, Vanderbilt University, Virginia Tech.). Others are faculty initiated efforts that gain administrative support, and some are created as a result of interdisciplinary groups going after large amounts of external funding: NSF-STCs, NSF-ERCs, NSF-NRTs, NOAA Cooperative Science Centers (CSCs), and NOAA Cooperative Institutes (CIs). In almost all cases these ORUs or IDPs co-exist with disciplinary departments that retain exclusive control over academic life through control over hiring and tenure, approval of courses and their development, requirements for degree, and criteria for merit evaluation. Such departmental control maintains the barriers that have been identified as hindering interdisciplinary efforts. The National Academies contends that few universities have implemented systematic reforms to lower institutional barriers to IDRE (NAS, 2004). A study that examined the interdisciplinary centers of major universities reported that “Universities are failing to walk the walk”- or even to comprehend fully what doing so would entail.” (NAS, 2004) Despite the rhetoric and apparent enthusiasm for crossing disciplines, interdisciplinary programs (IDPs and ORUs) remain relatively difficult to initiate, fund, and sustain.

In developing IDRE, several universities have implemented formal funding programs to support and establish ORUs by pooling resources centrally and redistributing them competitively (Sa, 2008). The funding is provided through seed grants as part of the strategic planning efforts aimed at self-sustainability after a few years. The Penn State and Stanford models steer faculty recruitment and time allocations towards certain interdisciplinary areas by enacting compulsory cost reductions in the academic units to fund strategic initiatives that lead to the creation of major institutes (Sa, 2008). The Penn State institutes were formed at the initiative of the central administration and are centrally funded to build research capacity in the strategic areas of the university. While faculty are appointed in academic units and research grants are managed through the schools and departments, the institutes are established to provide a single and visible face for decentralized scientific expertise on campus that is not captured by traditional departmental divisions (Sa, 2008). This has, however, continued to create tension between disciplinary departments and the institutes.

Such models provide a proof of concept case in which university leaders make strategic decisions about the direction of growth of the research enterprise by creating and supporting these units and effectively steering the course of institutional development. In almost every situation, IDRE requires a commitment from a university's administration. The centers' needs for faculty, space, and funds must be recognized by administrators. Through control of faculty positions, the university leadership can promote collaboration, for example, by requiring a position to be jointly supported and evaluated by two departments (Pellmar, 2002) or by ensuring that interdisciplinary programs do not drift back to a primarily single disciplinary perspective (Pellmar, 2002). None of the steps are, however, transformative enough to remove the barriers.

6. Recommendations

IDRE programs if properly done can be viewed as equivalent to "new business incubators." Administrative structures and procedures for allocating funds need to be completely rethought to promote collaboration across disciplines and colleges. For IDRE to flourish, for redundancies to be removed, and for lessons learned in one course to be transferable, disciplinary courses cannot be owned, managed, and controlled by individual disciplinary units.

For IDRE to succeed, action plans are needed to prepare faculty to recognize or value contributions from "outside" ones' discipline (Bruce et al., 2004; Larson & Begg, 2011). The current academic structure has been a serious hindrance to overcoming this problem. Lack of incentive to collaborate has prevented departments from creating a common language to improve communication.

It has been recommended that institutions reward leaders for initiating interdisciplinary programs and provide incentives for departments to share indirect cost revenues, seed money, course-credit assignments, intellectual property, space, personnel, and other resources. They can limit the degree to which reward structures are bound to disciplinary silos. However, this approach requires working within the existing structure, which is the very problem.

The recommendations made so far only try to tweak the current academic structure. They try to improve communication and the structures for providing rewards, funding, incentives, and course offerings. Creation of interdisciplinary centers, institutes, and degree programs that co-exist with the existing disciplinary structure does not change who controls the funding and the processes for tenure and promotion, and course development and approval. Reducing institutional structural and cultural barriers is not sufficient to move collaborative research forward.

What is needed is a new approach that will simultaneously allow disciplines to flourish and grow with unprecedented innovation brought about by open communication and collaboration with other disciplines. This new approach will remove duplication and help students transfer skills learned in one discipline to other disciplines. This new approach will allow educators and researchers to develop common language and standards, minimizing and even eliminating the language barrier. It reduces the number of middle management positions to allow resources to be fully used to improve learning and research.

We propose a structure based on the following premises:

1. Disciplinary expertise or credentials are determined by the number and level of courses that students take. They don't have to belong to a specific academic unit called the department or even college or school. A degree can be earned as long as institutions have the courses and the right faculty to teach them and based on the required number of credits taken by students.

2. Disciplinary courses and disciplinary experts can exist in a University without an administrative unit called the Department or the College. Courses should be taught by disciplinary experts but should be owned by the office of academic affairs not by disciplinary units. This will make it easier for content experts and users of these courses in other disciplines to collaborate easily in improving and revising the courses to make them accessible and relevant.
3. When faculty are not segregated by a department or a college but develop collaborations around a problem or issue, new knowledge, innovation, and good student learning outcomes can be insured, and new and innovative courses can be developed to help the entire institution.

In a time of shrinking budgets in higher education, university administrators want to cut programs and close departments based on enrollment numbers rather than the need and importance of the discipline for economic growth. The need to close a department to save an administrative position may motivate a decision, as opposed to serious consideration of the consequences.

6-a. University Course Development

Universities should conduct a comprehensive review of courses offered by different disciplines to identify gaps, redundancies, and relevance for both the present and the future. The review of the courses should be made by disciplinary experts in collaboration with other disciplines that could potentially require the courses in their specific disciplines to make sure knowledge in a given course is transferable. This is important in the introductory common courses like calculus, general physics, and general chemistry. A student who had a calculus course shouldn't have any trouble understanding the math used in general physics for example.

A redesign should also include identification of disciplinary core courses that should be available for everyone to pursue meaningful interdisciplinary training. Such course revision can be effective if the reward structure and budgeting is based on student credit hours generated and if efforts are made to reach out to other disciplines to develop new knowledge and new courses that utilize methodologies from multiple disciplines. This will encourage team teaching of courses, which will in turn help not only the learners (the students) but the faculty teaching the course to communicate and interact closely, facilitating the required development of a common language.

6-b. University IDRE

The interdisciplinary research centers and institutes should be developed independently of the academic units (Departments and Colleges) and need to be housed under the University research office. Research groups should be developed around issues and problems. Centers and institutes should be independently funded and independently administered. These research units should be structured to overcome stagnation by continuous assessment of the programs and the work force needs.

Research units should work closely with their academic counterparts and be encouraged to use new knowledge developed through IDRE to be incorporated into new interdisciplinary courses. Faculty who both advance their own discipline but also venture outside their discipline to collaborate and conduct IDRE should be rewarded. Universities should be held accountable in making sure federally funded large interdisciplinary centers are supported by policy and structural changes that will allow them to be sustainable.

7. Conclusion

Continued scientific and technological innovations are critical to fostering sustained economic growth and global competitiveness. The growing complexity of today's scientific problems along with advancements in science and technology demand greater interdisciplinary collaboration among researchers in all disciplines including non-STEM disciplines. This is amplified by the demand of the job market for interdisciplinary individuals, which in turn requires interdisciplinary training of students at all stages and interdisciplinary thinking of faculty and administrators.

The decline in the level of achievement and interest in STEM fields in the U.S. has resulted in an inadequate supply of workers with the desired STEM skills and education. We have argued that the decline of interest in STEM and the decline in the number of STEM graduates is a result of university academic structure. Any attempt to improve STEM education within the existing structure will likely lead to disappointing results.

Universities need to educate graduates who can excel and moreover adapt in an interdisciplinary and global workforce, not only in universities' and colleges' disciplinary units. Graduates seeking employment in industry require a much higher level of skills across different disciplines (Bunk, 1998). Over-specialization may create a barrier to employment. Opportunities to provide a broader skills base in graduate education and contact with industrial research should be explored. It should be noted that interdisciplinary education does not necessarily mean that a person become a parody of "interdisciplinarity" -lacking in any specific disciplinary knowledge or research direction- rather that he/she is able to work well with other disciplines, has respect for them, and is able and willing to seek them out when there is a need for another discipline.

The recommendations listed above are being implemented in some universities. We look briefly at three below: one public, UC Merced, and two private, Dartmouth College and Olin College. A single department brings together faculty with expertise in a range of engineering and science disciplines. Students are mentored by teachers who are not only experts in one or more fields but also generalists who can envision solutions that cut across traditional disciplines.

When UC Merced was established in 2005, it eschewed traditional department silos and majors in favor of an interdisciplinary organization (Kemsley, 2013). UC Merced features a unique academic structure that removes barriers to interdisciplinary research common in traditional departments and fosters strong ties with physical sciences research to life sciences, materials science, and engineering. When UC Merced opened, there were no departments. Faculty instead organized into units that defined six undergraduate majors and several interdisciplinary graduate groups. The overarching philosophy was to avoid being tied to traditional academic structures and instead to rethink curricula for the 21st century and promote interdisciplinary studies. For example, the school of natural sciences at UC Merced is organized around thematic categories to encourage cooperation and collaboration across disciplines. It is expected that government agencies, politicians, news organizations, community leaders and others will look to UC Merced for insights and guidance on emerging issues. For example, UC Merced is one of the recipients of the Council of Higher Education Accreditation (CHEA) award, an award that recognizes institutions that have been exceptional in developing and applying evidence of student learning outcomes to improve higher education quality and accountability.

Olin College was established in 2001with a generous endowment and hopes to break with tradition to produce technology-minded engineering entrepreneurs for the 21st century (Irving, 1998). Olin's radically new way of training engineers incorporates changes that many in industry and academia (reformers at the National Science Foundation (NSF) believe most American engineers tend to be narrow specialists, ill-equipped to fill top jobs in business or industry) say are long overdue. The College is not organized with traditional academic departments. Instead the faculty operates as a single interdisciplinary unit with offices assigned to faculty members without any regard to discipline. The College intends to develop a culture of innovation and continuous improvement (NAS, 2004). NSF has funded a project to study the outcome of the innovative engineering program at Olin, but the results have not yet been released. In 2013 Olin did receive the Bernard M. Gordon Prize for Innovation in Engineering and Technology Education given by the National Academy of Engineering. In 2013 starting salaries for Olin graduates were more than $18,000 above the U.S. national average for engineers.

At Dartmouth College, sponsored research increased from $67 million to $187 million from 1993 to 2006. Dartmouth's STEM graduate programs have experienced change in response to this increased infusion of funded research, with increases in size and overall scholarly productivity (NRC, 2010). Some Dartmouth programs were recently rated within the top 10 nationally.

We can learn from the innovative approaches at Dartmouth, Olin, and UC Merced. They demonstrate that radical university structural changes are more easily accomplished with startup colleges (e.g. Olin and UC Merced) but still possible with existing colleges (e.g. Dartmouth). They may also suggest that radical changes are more easily accomplished at private colleges (e.g., Olin and Dartmouth) than at public colleges (UC Merced).

To harness the nation's great scientific and technological potential, government, industrial, educational and research organizations need to work together to improve and radically change the university structure. The structural change is needed to improve the state of STEM education and allow the integration of disciplines to foster strong interdisciplinary collaboration among the various disciplines. This change will allow training interdisciplinary individuals needed for the 21st century and disciplines to grow. Such training is critical for the production of sustainable and innovative solutions to society's most pressing challenges.

Acknowledgment

The authors acknowledge the support of the National Science Foundation Grant # NSF-DMS-1016591 (Roop), Grant #NSF-DUO-1035729 **(**Bililign), and Grant #NSF-HRD-1242152 (Schimmel). Bililign acknowledges the stimulating discussions and comments by Dr. James Roberts- NOAA Earth System Research Laboratory.

References:

Aboelela, S.W., Larson E, Bakken S, Carrasquillo O, Formicola A, Glied SA, Haas J, Gebbie KM. (2007). Defining interdisciplinary research: conclusions from a critical review of the literature. *Health Serv Res. , 42*(1), 329-346.

Adrianna Kezar, Jaime Lester. (2009). *Organizing Higher Education for Collaboration: A Guide for Campus Leaders*. San Fransisco, CA: Jossey Bass.

Alpert, D. (1969). *The Role and Structure of Interdisciplinary and Multidisciplinary Research Centers*. Paper presented at the Address at the Ninth Annual Meeting of the Council of Graduate Schools Washington DC.

Amabile, Teresa M., Patterson, Chelley, Mueller, Jennifer, Wojcik, Tom, Odomirok, Paul W., Marsh, Mel, & Kramer, Steven J. (2001). Academic-Practitioner Collaboration in Management Research: A Case of Cross-Profession Collaboration. *The Academy of Management Journal, 44*(2), 418-431.

Anbar, M. (1986). The "bridge scientist" and his role. In A. L. P. D. E. Chubin, F. A. Rossini, & T. Connolly (Ed.), *Interdisciplinary analysis and research: Theory and practice of problem-focused research and development* (pp. 155–163). Mt. Airy, MD: Lomond Publications, Inc.)

Barrick, Murray R.; Stewart, Greg L.; Neubert, Mitchell J.; Mount, Michael K. (1998). Relating member ability and personality to work-team processes and team effectiveness. *Journal of Applied Psychology, 83*(3), 577-391.

Berry, Barnett; Johnson, Dylan; Montgomery, Diana. (2005). The Power of Teacher Leadership. *Educational Leadership, 62*(5).

Brewer, GarryD. (1999). The challenges of interdisciplinarity. *Policy Sciences, 32*(4), 327-337. doi: 10.1023/A:1004706019826

Bruce, Ann, Lyall, Catherine, Tait, Joyce, & Williams, Robin. (2004). Interdisciplinary integration in Europe: the case of the Fifth Framework programme. *Futures, 36*(4), 457-470. doi: http://dx.doi.org/10.1016/j.futures.2003.10.003

Bunk, S. . (1998). Young scientists face demand for broader-based education. *Scientist, 12,* 12-13.

Caruso, D.; Rhoten D. (2001). Lead, follow, get out of the way: sidestepping the barriers to effective practice of interdisciplinarity. The Hybrid Vigor Institute

Clark, B. . (1995). *Places of inquiry: Research and advanced education in modern universities*. Berkeley, CA: University of California Press.

Cooley, Elizabeth. (1994). Training an Interdisciplinary Team in Communication and Decision-Making Skills. *Small Group Research, 25*(1), 5-25. doi: 10.1177/1046496494251002

Cui, L. . (2006). *Assessing College Students Retention and Transfer from Calculus to Physics.* (PhD), Kansas State University.

Derrick, E. G. Holly J. Falk-Krzesinski, Melanie R. Roberts,. (2012). Facilitating Interdisciplinary Research and Education: A Practical Guide. http://www.aaas.org/report/facilitating-interdisciplinary-research-and-education-practical-guide

Eagan, Patrick, Cook, Tanya, & Joeres, Erhard. (2002). Teaching the importance of culture and interdisciplinary education for sustainable development. *International Journal of Sustainability in Higher Education, 3*(1), 48-66. doi: doi:10.1108/14676370210414173

Fay, Doris, Borrill, Carol, Amir, Ziv, Haward, Robert, & West, Michael A. (2006). Getting the most out of multidisciplinary teams: A multi-sample study of team innovation in health care. *Journal of Occupational and Organizational Psychology, 79*(4), 553-567. doi: 10.1348/096317905X72128

Feller, Irwin. (2002). New organizations, old cultures: strategy and implementation of interdisciplinary programs. *Research Evaluation, 11*(2), 109-116. doi: 10.3152/147154402781776862

Feller, Irwin. (2006). Multiple actors, multiple settings, multiple criteria: issues in assessing interdisciplinary research. *Research Evaluation, 15*(1), 5-15. doi: 10.3152/147154406781776020

Fritz, S. (2002). *Understanding nanotechnology* New York: Warner Books.

Frykholm, Jeffrey, & Glasson, George. (2005). Connecting Science and Mathematics Instruction: Pedagogical Context Knowledge for Teachers. *School Science and Mathematics, 105*(3), 127-141. doi: 10.1111/j.1949-8594.2005.tb18047.x

Gallagher, William Stepien and Shelagh. (1993). Problem-Based Learning: As Authentic As It Gets. *Educational Leadership, 50*(7).

Gardner, Howard. (2006). *Five minds for the future*. Boston, MA: Harvard Business School Press.

Gazzaniga, Michael S. (1998). How to Change the University. *Science, 282* (5387).

Giri, Ananta Kumar. (1998). Transcending Disciplinary Boundaries: Creative experiments and the critiques of modernity. *Critique of Anthropology, 18*(4), 379-404. doi: 10.1177/0308275x9801800402

Golde, Chris M., & Gallagher, Hanna Alix. (1999). The Challenges of Conducting Interdisciplinary Research in Traditional Doctoral Programs. *Ecosystems, 2*(4), 281-285. doi: 10.1007/s100219900076

Golding, C. (2009). *Integrating the Disciplines: Successful Interdisciplinary Subjects*. University of Melbourne: Centre for the Study of Higher Education.

Gooch, J. (2005). The dynamics and challenges of interdisciplinary collaboration: A case study of "cortical depth of bench" in group proposal writing. *IEEE Transactions on Professional Communication,, 48*.

Groark, C. J., & McCall, R. B. . (1996). Building successful university-community human service agency collaborations. In J. P. M. C. B. Fisher, & I. E. Sigel (Ed.), *Applied developmental science: Graduate training for diverse disciplines and educational settings.* (Vol. 13, pp. 237-251). Norwood, NJ: Ablex Pub. Corp.

Heberlein, Thomas A. (1988). Improving interdisciplinary research: Integrating the social and natural sciences. *Society & Natural Resources, 1*(1), 5-16. doi: 10.1080/08941928809380634

Henry, S. . (2005). Disciplinary hegemony meets interdisciplinary ascendancy: Can interdisciplinary/integrative studies survive, and if so, how? . *Issues in Integrative Studies, 23*.

Irving, C. . (1998). Well-educated Bricklayers?Two new colleges hope to produce broadly trained engineers. *National Cross Talk*. http://www.highereducation.org/crosstalk/ct0198/news0198-bricklayers.shtml

Ivanitskaya, Lana, Clark, Deborah, Montgomery, George, & Primeau, Ronald. (2002). Interdisciplinary Learning: Process and Outcomes. *Innovative Higher Education, 27*(2), 95-111. doi: 10.1023/A:1021105309984

Jacobs, N. (2009). The interdisciplinary hype. *The Chronicle of Higher Education, 22,* B4-B5.

Jeffrey, Paul. (2003). Smoothing the Waters: Observations on the Process of Cross-Disciplinary Research Collaboration. *Social Studies of Science, 33*(4), 539-562. doi: 10.1177/0306312703334003

Kemsley, J. . (2013). UC Merced turns 10. *Chemical and Engineering News, 91,* 32-33.

King CR, McGuire DB, Longman AJ, Carroll-Johnson RM. (1997). Peer review, authorship, ethics, and conflict of interest. *Image J Nurs Sch., 29*(2).

Klein, J. T. . (1996). *Crossing boundaries: Knowledge, disciplinarities, and interdisciplinarities*. Charlottesville, VA: University Press of Virginia.

Kumar Giri, Ananta. (2002). The calling of a creative transdisciplinarity. *Futures, 34*(1), 103-115. doi: http://dx.doi.org/10.1016/S0016-3287(01)00038-6

Larson, Elaine L., & Begg, Melissa D. (2011). Building Interdisciplinary Research Models: A Didactic Course to Prepare Interdisciplinary Scholars and Faculty. *Clinical and translational science, 4*(1), 38-41. doi: 10.1111/j.1752-8062.2010.00258.x

Lattuca, Lisa R. (2002). Learning Interdisciplinarity: Sociocultural Perspectives on Academic Work. *Journal of Higher Education, 73*(6).

Leshner, A. I. (2004). Science at the leading edge. *Science,, 303*.

Mansilla, Veronica Boix, Feller, Irwin, & Gardner, Howard. (2006). Quality assessment in interdisciplinary research and education. *Research Evaluation, 15*(1), 69-74. doi: 10.3152/147154406781776057

Massey, Claire, Alpass, Fiona, Flett, Ross, Lewis, Kate, Morriss, Stuart, & Sligo, Frank. (2006). Crossing fields: the case of a multi-disciplinary research team. *Qualitative Research, 6*(2), 131-147. doi: 10.1177/1468794106062706

Meredith, Dawn C., & Bolker, Jessica A. (2012). Rounding off the cow: Challenges and successes in an interdisciplinary physics course for life science students. *American Journal of Physics, 80*(10), 913-922. doi: doi:http://dx.doi.org/10.1119/1.4733357

Meredith, Dawn C., & Redish, Edward F. (2013). Reinventing physics for life-sciences majors. *Physics Today, 66*(7), 38-43. doi: doi:http://dx.doi.org/10.1063/PT.3.2046

MOORE, MARY NEEDHAM. (1989). Tenure and the University Reward Structure. *Nursing Research, 38*(2), 111-116.

Naomi Jacobs, Martyn Amos. (2010). Removing Barriers to Interdisciplinary Research. *arXiv:1012.4170*.

NAS. (2004). *Facilitating Interdisciplinary Research examines current interdisciplinary research efforts and recommends ways to stimulate and support such research.*

NRC. (2012). Education for Life and Work: Developing Transferable Knowledge and Skills in the 21st Century. In J. W. P. a. M. L. Hilton (Ed.), *Committee on Defining Deeper Learning and 21st Century Skills*. Washington DC: The National Academies Press.

Pellmar, T.C. & Eisenberg, L. (Eds.). (2002). *Bridging disciplines in the brain, behavioral, and clinical sciences.* . Washington, DC: National Academies Press (US.

Pfister, Christian. (2007). Climatic Extremes, Recurrent Crises and Witch Hunts: Strategies of European Societies in Coping with Exogenous Shocks in the Late Sixteenth and Early Seventeenth Centuries. *The Medieval History Journal, 10*(1-2), 33-73. doi: 10.1177/097194580701000202

Pickett, S. T. A., Burch, William R., & Grove, J. Morgan. (1999). Interdisciplinary Research: Maintaining the Constructive Impulse in a Culture of Criticism. *Ecosystems, 2*(4), 302-307.

Rhoten, Diana. (2003). A multi-method analysis of the social and technical conditions for interdisciplinary collaboration (Vol. BCS-0129573). Arlington VA: Final report National Science Foundation BCS-0129573

Rhoten, Diana. (2004). Interdisciplinary Research: Trend or Transition. *Items & Issues, 5*, 6-11.

Rhoten, Diana, & Parker, Andrew. (2004). Risks and Rewards of an Interdisciplinary Research Path. *Science, 306*(5704), 2046-2046. doi: 10.1126/science.1103628

Rogers, S., Booth, M., & Eveline, J. . (2003). The Politics of Disciplinary Advantage. *History of Intellectual Culture, 3*(1).

Sa, Creso M. (2008). University-Based Research Centers: Characteristics, Organization, and Administrative Implications. *Journal of Research Administration, 39*(1), 32-40

Shinn, Marybeth. (2006). External, Not Internal Challenges to Interdisciplinary Research. *American Journal of Community Psychology, 38*(1-2), 27-29. doi: 10.1007/s10464-006-9057-0

Siedlok, F., & Hibbert, P. . (2009). *Interdisciplinary research: A review of contextual and process factors.* Paper presented at the Australia and New Zealand Academy of Management: Sustainable Management and Marketing, Melbourne, Australia.

Stepien, William; Gallagher, Shelagh. (1993). Problem-Based Learning: As Authentic as It Gets. *Educational Leadership, 50*(7).

Susan H. Frost, Paul M. Jean. (2003). Bridging the Disciplines: Interdisciplinary Discourse and Faculty Scholarship. *The Journal of Higher Education 74*(2).

Taylor, M. (2009). End the university as we know it, *The New York Times*.

Tuminaro, J. . (2004). *A cognitive framework for analyzing and describing introductory students' use and understanding of mathematics in physics.* (PhD), University of Maryland.

Van Hartesveldt, C. & Giordan, J. . (2008). Impact of transformative interdisciplinary research and graduate education on academic institutions *NSF 09-33, IGERT Workshop Report* Arlington, VA: National Science Foundation.

Wear, David N. (1999). Challenges to Interdisciplinary Discourse. *Ecosystems, 2*(4), 299-301.

Weiner, G. . (1998). *Scholarship, disciplinary hegemony and power in academic publishing*. Paper presented at the the European Conference for Educational Research.

Young, K. (2000). What makes transdisciplinarity succeed or fail? Second report. In M. A. Somerville and D. J. Rapport (Ed.), *Transdisciplinarity: recreating integrated knowledge* (pp. 218-220). Oxford, UK: EOLSS Publishers Ltd.

Zeidler, DanaL. (2002). Dancing with Maggots and Saints: Visions for Subject Matter Knowledge, Pedagogical Knowledge, and Pedagogical Content Knowledge in Science Teacher Education Reform. *Journal of Science Teacher Education, 13*(1), 27-42. doi: 10.1023/A:1015129825891