NATIONAL BIOECONOMY BLUEPRINT
Response to Request for Information: Building A 21st Century Bioeconomy

Prepared by Tufts University

Introduction

Biological research throughout the United States is a crucial aspect of the national economy, through the staff employed by laboratories in universities and other research institutions, through the operation of research facilities, as well as the application of the knowledge created. Currently, Tufts University employs approximately 600 faculty engaging in research and education that supports the bioeconomy, from basic scientists to clinical researchers and practitioners to those involved in the development of policy as research moves into the marketplace. Supporting our faculty are many more (over 3,000) laboratory assistants and technicians, administrators serving labs, departments, schools and the university, librarians, and those devoted to facilities maintenance, security, and infrastructure. Tufts also has currently more than 9,500 graduate and professional students enrolled, and more than 2,500 of these are in biomedical fields, with many others in fields that have applications to biomedical science. These students play a tremendous role at Tufts, both as the scientists of the future, and as one way in which new collaborations are formed, both informally and through formal educational initiatives.

As with many research intensive institutions throughout the US, Tufts University faces a range of challenges with regards to extramural funding and translating research to the marketplace. With budgets of Federal funding agencies continuing to be flat or even reduced, we will continue to face challenges of how to continue to conduct innovative and transformative research in the fields of basic and clinical biomedical research and policy. Tufts has an immensely diverse research portfolio, and is characterized by its priority for collaboration across the various Schools and Centers. We seek to support this research program, and to look for new and creative ways to ensure that our research program continues to grow and, ultimately, to support the bioeconomy of our region and beyond.

Team science in the biomedical sciences is a tremendous cultural shift for the discipline, particularly with regards to integration with such diverse fields as mathematics, physics, modeling, and computer sciences. One hurdle that such teams face is the physical organization of scientists. While technologies have increased the degree to which researchers can collaborate over distance, the formation of teams is facilitated primarily by physical proximity. Programs that both provide incentives for new interdisciplinary teams to form and that provide a space for scientists to formally and informally meet and discuss their research projects are essential to the development of cutting edge team science.

Over the past several years, Tufts has worked to address this challenge, and to strengthen the bioeconomy in our region through increasing and improving our research infrastructure. In 2009, Tufts Cummings School of Veterinary Medicine opened the New England Biocontainment Laboratory. Built with funds from NIH, this BSL-3 laboratory serves Tufts, other New England universities, and the private sector for the study of infectious diseases as well as for biodefense research. Also in 2009, Tufts University School of Dental Medicine opened its 5-story, 95,500 sq ft LEED-certified expansion on top of the existing School's building. This space supports additional training and research efforts, in addition to adding 73 new treatment centers, with the capacity to care for 20,000 patients a year, many of whom have no or limited dental insurance. In 2009, the School of Engineering opened the Proof of Principle Lab to support collaborations between the university and industry and promote translation in areas including tissue development, drug delivery, optics, and optoelectronic technologies.

With $1.6 million from the NSF, the Tufts Department of Civil and Environmental Engineering is creating a state-of-the-art Environmental Sustainability Lab that will support multidisciplinary experimental and mathematical modeling research on such issues as the effects of nanoparticles and pharmaceuticals in water, soil and other media. The Department of Biology in the School of Arts & Sciences has received funds from NIH to support the creation of new laboratories that will allow for more collaboration and integration of its basic and translational research programs. Tufts also has plans to expand core facilities to support an increased need expressed from faculty and is working to renovate existing laboratory spaces throughout the Boston Health Sciences Campus.

These construction projects support a growing biological and biomedical research community at Tufts University. This growth is due to initiatives at the School and Central Administration level to support multidisciplinary and collaborative research projects. In 2005, the Office of Proposal Development was created to support groups of faculty to write and submit multidisciplinary proposals. In 2008, Tufts received an NIH Clinical and Translational Sciences Award for the creation of the Clinical and Translational Sciences Institute, which provides resources for faculty throughout the university to reduce the barriers for multidisciplinary research projects. Additionally, in 2010, the Provost instituted the Tufts Collaborates! seed grant program, to provide new groups of faculty with the funds necessary to develop preliminary data and solidify new interdisciplinary collaborations.

Research is not only part of the bioeconomy, but it is also the very foundation from which the bioeconomy must build its success, and any national blueprint must incorporate an aggressive and robust research portfolio to bolster efforts to expand the bioeconomy.

Grand Challenges

Question 1: Identify one or more grand challenges for the bioeconomy in areas such as health, energy, the environment, and agriculture, and suggest concrete steps that would need to be taken by the Federal government, companies, nonprofit organizations, foundations, and other stakeholders to achieve this goal.

In an increasingly globalized society, the bioeconomy is, by necessity, connected through many layers, from international trade and commercialization to regional efforts to local universities. These layers, however, are not well integrated at this point, and there are barriers at each level to developing and supporting research that has global impact. These include access to investment capital as well as fair and reasonable approaches to intellectual property rights. Chief among these barriers is the so-called "valley of death" – limited amounts of capital to support the development of early stage discoveries, curtailing or even obliterating the opportunity for innovative discoveries to reach the market place.

Addressing grand challenges requires a genuinely interdisciplinary approach and requires input from both individual researchers and large multidisciplinary centers. One barrier to such collaborations is the current mechanisms for funding. Federal research funding opportunity announcements increasingly state that programs seek interdisciplinary approaches to currently intractable scientific problems. However, mechanisms for funding such large programs (e.g., NIH's program project grants) are used infrequently by many Institutes and Centers. Furthermore, without mechanisms to support collaborations in advance of these larger awards, individual researchers see little benefit in forming interdisciplinary groups far enough in advance of potential funding opportunities to be competitive. Specific RFAs from NIH and USAID (in particular) and NSF (to a lesser degree) are released with little time for groups to form – researchers must already have in place substantial preliminary work and evidence of existing collaborations to be competitive – and the current system of releasing one-time RFAs for particular challenges does not encourage new and potentially highly innovative collaborations to form, but rather rewards existing collaborations.

Grand challenges should be identified through a fully interactive process involving Federal agencies, academia and industry, similar to NAE Grand Challenges for Engineering. Through a multilevel process involving multiple stakeholders, Grand Challenges can be targeted both to national need and to feasibility. This process can likewise encourage academic, industry, and community stakeholders to work together to eliminate barriers to bringing findings from these Grand Challenges to the marketplace in an efficient and effective manner. Ideally, this process should involve discussion, both through online technologies similar to discussion boards and wikis and through real-time webcasts or similar formats, in addition to more traditional Requests for Information. In this way, a genuine conversation can occur, and questions can be posed and answered more immediately.

A crucial need exists to coordinate and network existing research, involving universities, industry and non-profits, to maximize the impact of the research and to address the Grand Challenges. These 'bioeconomy consortia' must have minimal barriers to participation. One way to encourage these multi-institutional consortia is to adopt a Federal-wide approach to proposal submission similar to NSF's 'collaborative' proposals. Instead of requiring a lead institution and subcontracts for other participating institutions, NSF allows, for many funding opportunities, two institutions to supply independent yet linked budgets and other materials. Thus, each institution has the ability to request full indirect costs, the lead institution has reduced administrative burden, and each institution is seen as an equal partner in the research endeavor.

Research and Development

Question 2: Constrained Federal budgets require a focus on high-impact research and innovation opportunities. With this in mind, what should be the federal funding priorities in research technologies and infrastructure to provide the foundation for the bioeconomy?

Traditional life sciences and basic research must be included in the bioeconomy blueprint. While basic science research has popularly been known as "seeking knowledge for knowledge's sake," this research provides the foundation on which the bioeconomy rests. Basic research is frequently the venue through which therapeutic targets are uncovered, and the concept of personalized medicine indicates that we are still lacking an understanding of potential therapeutic targets. A number of Tufts scientists are currently supported by Federal funding to conduct basic science that has great promise for future marketable products. For instance, Abraham L. Sonenshein is investigating the mechanisms by which two related bacterial species control the flow of metabolites between central carbon and central nitrogen pathways, thus allowing a deeper understanding of pathogenic mechanisms and may aid in designing novel inhibitors of pathogenesis. Jonathan Garlick studies the potential for pluripotent human embryonic stem cells to bioengineer oral mucosa for regenerative medicine. Philip Haydon is investigating the role of astrocytes in regulating neuronal receptors that are essential for synaptic plasticity and learning and memory. These receptors are thought to be involved in several disorders, and his research may lead to the identification of novel therapeutic targets. David Kaplan researches at the interface between biology and materials science and engineering to understand and control biological synthesis and the processing of biopolymers. Studies focus on the manipulation of human cells on novel matrices in bioreactors to generate desired tissue outcomes for engineered tissue replacements and 3D disease models for therapeutic drug discovery.

Additionally, basic research in the bioeconomy includes such areas as computational epidemiology, biosensing, and green energy. Elena Naumova's multidisciplinary work in the fields of computational epidemiology, conservation medicine, and biostatistics improve the quality of basic biomedical research with analytical tools for researchers and policy makers. Fiorenzo Omenetto, with David Kaplan, has identified bio-friendly polymers to serve as platforms for optical and electronic components that seamlessly integrate with the environment and with living tissue. By exploiting these biopolymers to produce mechanically robust, biodegradable technological materials platforms, a new generation of flexible electronic and optical systems and devices for medical and environmental applications can be developed. Matt Panzer's research efforts are motivated by the challenge to capture, convert, and store solar energy with nanostructured thin film photovoltaics to develop novel solutions that meet global energy demands.

Complementary approaches are necessary to drive innovation and address the underlying questions on which the clinical needs rest. Both funding for single topic areas in basic research and for multidisciplinary (and multi-agency) translational science programs are necessary, particularly to pursue breakthroughs in personalized medicine. One approach from NIH has been to ask applicants to describe the relevance to human health of the proposed research. While this method of ensuring that NIH's mandate is met is necessary, it has resulted in the perception that basic research is less valued and less likely to be funded in a highly competitive environment. At the same time that the budgets of

Federal agencies are unstable, NIH has, under Dr. Francis Collins' direction, introduced an increased priority on immediately translational research. Many basic science researchers view this direction as a betrayal of the work they do. To ensure that basic biomedical research continues, other agencies may need to have increased funding specifically for this sort of research.

Furthermore, much basic research does have a more immediate connection to potentially marketable applications. For these researchers, multi-agency, multidisciplinary funding opportunities can have a tremendous impact. An example of this sort of program is the NSF/NIH Evolution and Ecology of Infectious Diseases solicitation. This program seeks multidisciplinary teams that can approach the question of infectious disease transmission dynamics in many ecosystems and for all life forms, including zoonotic and plant disease as well as links to human health. Through mechanisms such as these, basic scientists can partner with clinical researchers, epidemiologists, social scientists, clinicians, and others to gain a broader understanding of both the underlying mechanisms and the environmental factors for disease transmission, thus providing the broader scientific community and policy makers to be able to predict and respond to future outbreaks.

Despite constrained budgets, high-risk, high-reward research must be supported. NIH has a mechanism by which these projects can be funded: the Exploratory/Developmental Research Grant Award (R21). However, the R21 mechanism, through which researchers can request up to $275,000 for up to 2 years, is often seen by both researchers and reviewers alike as a "mini" research grant, and the expectation for substantial preliminary data (which are technically not required) prevents many researchers who wish to explore a new direction from applying for this mechanism. To ensure that these potential breakthrough ideas receive adequate funding, the review system for R21 proposals should be revised, through separate panels and an increased focus on the existing "innovation" review criteria. Additionally, the Small Grant (R03) program should be expanded to fill the role that the R21 is by default filling – to provide a way in which additional preliminary data can be developed in preparation for a larger research grant.

Research funding should support truly interdisciplinary projects where all disciplines drive the research. A high-impact initiative of Tufts University is the Jean Mayer USDA Human Nutrition Research Center on Aging. As the largest research center in the world investigating nutrition and its role in age-related chronic and infectious diseases, the HNRCA's research is supported by Agricultural Research Service (ARS), the intramural research arm of the USDA, as well as by other federal and, to a far lesser extent, non-federal grants. Twenty research laboratories, supported by 270 researchers, trainees and staff as well as nine Core Units, comprise the HNRCA. While all research conducted at the HNRCA is related to the overall themes of nutrition and aging, these labs employ diverse research methods, including cellular and molecular studies, animal studies, human metabolic studies and epidemiological research, thus increasing the HNRCA's capacity for truly transformative and translational research. The current Strategic Plan released this year notes seven scientific priorities for the next five years:

- Nutrition and Neuroscience
- Nutrition and Functional Genomics
- Obesity and Aging
- Nutrition and Chronic Diseases of Aging, with a focus on Cancer and Cardiovascular Disease
- Inflammation, Immunity, Infectious Disease and Aging
- Musculo-Skeletal Defects Leading to Decline in Function in the Elderly
- Micronutrients and Healthy Aging

Each of these areas necessitates a multidisciplinary and collaborative approach, and will require the creation of teams within the HNRCA and between the HNRCA and the other Tufts Schools, including Engineering and Medicine, and between the HNRCA and external partners, including industry and non-profit organizations. Because of the HNRCA's commitment to use its research findings to educate the public, healthcare providers, policy makers, industry and the scientific community in related fields, the impact this Center can have will continue to be felt nationally and globally.

Likewise, the School of Engineering receives federal and non-federal funding in support of cross-cutting strategic areas selected to provide opportunity for societal impact. This includes engineering for human health, sustainability, and the human/technology interface. A component of this – Water: Systems, Science, and Society (WSSS) – provides unlimited collaborations. The WSSS encompasses participants from five of Tufts graduate schools, tackling challenges from coastal flooding to the spread of infectious disease.

Question 3: What are the critical technical challenges that prevent high throughput approaches from accelerating bioeconomy-related research? What specific research priorities could address those challenges? Are there particular goals that the research community and industry could rally behind (e.g., NIH $1,000 genome initiative)?

The critical technical challenges needed to advance high throughput approaches include data management, imaging, and design of new materials and technologies.

Through its Molecular Libraries Program and other research activities that will be part of the new National Center for Advancing Translational Sciences (NCATS), NIH is supporting several projects that use high throughput technologies in genetics and drug discovery. These activities will certainly help to accelerate translational research programs that could result in drug development. For instance, many researchers at Tufts work on the discovery of targets for drug discovery. Daniel Jay receives NIH support for his research on cancer and the mechanisms through which cancer is dispersed. This research allows the prediction of optimal drug regimens, complementing pharmacogenomics. But to advance Dr. Jay's research so that it will reach the clinic, Dr. Jay will need to collaborate with a biopharmaceutical company that can help him to optimize drug candidates. In collaborations such as this, one that will translate basic research into clinical compounds, it will be necessary for both parties to share reagents and collaborate openly, and to recognize the value of intellectual property that may be jointly owned.

A major challenge is to manage and interpret large volumes of data. Tufts University has a number of resources available to researchers to approach this challenge. The NIH-funded Tufts Center for Translational Sciences Institute (CTSI) supports both the Biomedical Informatics component, which provides the infrastructure for communication among CTSI researchers, and the Research Design Center, which assists researchers in study design, the creation of secure data collection systems, and data analysis. Additionally, Tufts University Information Technology recently launched a new research cluster that harnesses the power of many computers, called nodes. With the improved 64-bit cluster, a researcher can do more calculations in a shorter amount of time than by using only one computer. The NSF-funded VisWall, the centerpiece of Tufts' Center for Scientific Visualization, further provides researchers with ways of analyzing data. The state-of-the-art rear projection system allows researchers to create 3D models of data, and it has been used in such fields as fluid dynamics, geotechnical engineering, human factors in medical systems, image reconstruction and tomography, computational geometry, robotics, chemical mechanical planarization, computational anatomy and visualization itself.

Adding new technologies is essential to this part of the research enterprise, and computer systems for data analysis and management have advanced with tremendous speed. In response, Federal agencies should support the acquisition of such systems for academic institutions, individually or in consortia with other institutions and industry. Because the technological capabilities change rapidly, proposals for such systems should be reviewed and funds released as quickly as is practical. In this way, the research infrastructure throughout the United States can be substantially improved, allowing for greater ease of inter-institutional collaborations, data sharing, and data management.

Question 4: The speed of DNA sequencing has outstripped advances in the ability to extract information from genomes given the large number of genes of unknown function in genomes; as many as 70% of genes in a genome have poorly known or unknown functions. All areas of scientific inquiry *that utilize genome information could benefit from advances in this area. What new multidisciplinary funding efforts could revolutionize predictions of protein functions for genes?*

To revolutionize the prediction of protein functions for genes requires the construction and analysis of models of large, nonlinear dynamic networks that span several spatial and temporal scales. Multidisciplinary, multi-agency funding efforts are needed to develop multi-scale modeling that can integrate genomics data with environmental, protein, and network data to elucidate connections and fully understand biological systems. One example of collaborative research funding in this area is the NSF Division of Mathematics Sciences (DMS) program with the NIH National Institute of General Medical Sciences. This program funds projects on the application of mathematics to biomedicine. Currently, Tufts has mathematicians working on such problems, including Christoph Börgers who is funded through the NIH/NSF Collaborative Research in Computational Neuroscience program and, with mathematics professor Scott MacLachlan, through the NSF.

In addition to technological advances, to increase the capacity to extract information from genomes requires human capital. Increasingly, this gap is apparent in many quantitative fields (see, for instance, the “crowd-sourcing” of data analysis in such diverse fields as the Search for Extraterrestrial Intelligence, the identification of whale songs, and even a multiplayer online game to solve problems in protein folding). For biomedical research, however, there is an increasing need for those trained to help biologists understand existing data. As discussed below (see Workforce Development), most Federal funds to support training are for the doctoral level and above. To fill this need for additional human capital, Federal agencies can support those pursuing master’s degrees in fields crucial to understanding these existing data, in addition to continuing to support doctoral and postdoctoral training.

Moving Life Sciences Breakthroughs from Lab to Market

Question 5: What are the barriers preventing biological research discoveries from moving from the lab to commercial markets? What specific steps can Federal agencies take to address these shortcomings? Please specify whether these changes apply to academic labs, government labs, or both.

There are a number of barriers preventing research discoveries from moving from the lab to commercial markets. Often, university faculty may not be aware of the steps they will need to take to optimize their discoveries, particularly if they are working on new chemical entities or novel biologic therapies. An entrepreneurial ecosystem within the university can accelerate commercialization of basic research by providing investigators access to resources such as venture mentoring, angel investors, and business advisors, all with the goal of developing and maximizing the value of university intellectual property.

A second barrier is lack of proof of concept funding to help technologies and inventions bridge the “valley of death.” Federal funds can help to bridge this important gap in translational research, in part through changes to SBIR and STTR programs, as described below.

Question 6: What specific changes to Federal Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs would help accelerate commercialization of Federally-funded bioeconomy-related research?

To help to address the "valley of death" for early stage discoveries, changes in the SBIR and STTR programs can provide greater support to researchers in the early stages of discovery. For instance, more flexibility in the SBIR program for proof of concept funding or pre-incorporation activities could allow these investigators to bring their research to a stage where they will be seen as a lower risk investment for venture capital firms or other private entities.

Likewise, STTR funds could be used for patent protection and proof of concept programs, replicating the success of organizations and approaches such as the Coulter Foundation. The Coulter Foundation provides funds to biomedical engineering departments, and oversight committees are formed at each university with representatives from the medical school, the Office of Technology Transfer, entrepreneurs, local Venture Capital, and the Business school. With these stakeholders' involvement, the advances in biomedical engineering have a greater likelihood of surviving the "valley of death."

Question 8: What are the challenges associated with existing private-sector models (e.g., venture funding) for financing entrepreneurial bioeconomy firms and what specific steps can agencies take to address those challenges?

Currently, venture funding is de-risking investment, in part due to the US economic difficulties; as a result, limited venture capital funds are focused more on later stage technologies. Federal funding in the form of larger amounts of SBIR funding so that biopharmaceuticals can be sufficiently de-risked would help to address this. In this way, Federal funding can act as a catalyst to bring private money and risk capital to the table.

Additionally, new federal programs can be created within existing funding streams to leverage angel investors or venture funds. One possibility is to create a federal proof-of-concept center, or a core facility that can be accessed by SBIR-funded companies. These resources will help to bridge current gaps, while making start-ups more attractive to venture funds.

Workforce Development

Question 9: The majority of doctorate recipients will accept jobs outside of academia. What modifications should be made to professional training programs to better prepare scientists and engineers for private-sector bioeconomy jobs?

Training for scientists and engineers should explicitly foster skills needed for the bioeconomy workforce. These skills include the ability to work in diverse teams that straddle expertise areas and disciplines, innovative thinking oriented toward solving real-world problems, and communication with non-scientists. Most support for such training is at the doctoral level and above.

Currently, Tufts has approximately 12 NIH-funded institutional training grants, each of which offers the opportunity for predoctoral students to engage in cutting edge interdisciplinary research and training. For instance, as a researcher at the HNRCA and faculty member at the Friedman School of Nutrition Science and Policy, Dr. Andrew Greenberg's T32 focuses on nutrition as an underlying component of many chronic diseases and his training program gives the next generation of researchers the tools to address chronic disease prevention at the molecular, cellular, organismal and/or population levels. Similarly, Dr. Alice Lichtenstein, HNRCA research scientist and Friedman School faculty member, leads a predoctoral training program in nutrition and cardiovascular disease at the basic, clinical, epidemiological and/or translational level. Dr. James Schwob of the Tufts University School of Medicine leads an NIH-funded training program that is specifically designed for MD/PhD students and to bridge the communication and cultural divide that too often separates scientists and clinicians, thus providing students with the tools they need to successfully meld the two arenas.

To supplement these excellent training programs, support for those pursuing master's degrees should be available. Currently, there is an ongoing discussion about the future of the biomedical workforce, most notably illustrated by the recent NIH RFI on the topic. At Tufts and other institutions, there is a need for training at the master's level and below to train excellent scientists who can be a part of a support team for PhD-level scientists, as laboratory technicians, data miners, and experts in modeling, mathematics, and computer science. Many have noted a glut of PhD-level scientists, and the current training grants available, as well as the culture in many fields of awarding MS degrees to those who do not complete a PhD as a sort of "consolation prize," reinforces the idea that the PhD track is the only acceptable pathway to a career in biomedicine or related fields. Programs like the NIH T32 could be adapted for MS programs, and programs such as NSF's IGERT could be expanded to include MS students as well as PhD students. For each of these, the priority for funds should be for those training programs that have a truly interdisciplinary focus.

Scientists and engineers in both academia and industry will need appropriate awareness of the interdisciplinary research questions central to the bioeconomy. It will be critical to train biological scientists with highly developed quantitative skills, as well as physical scientists and engineers with appropriate awareness of challenges in the life sciences. Federal programs should support university efforts to develop curricula and programs focused on horizontal integration of training across disciplines while maintaining appropriate in-depth training in students' core research areas. Tufts has a demonstrated commitment to STEM education throughout the pipeline. For instance, faculty in the Department of Biomedical Engineering involve high school, undergraduate, and graduate students in team research, and many of these are from underrepresented groups. Additionally, Henry Wortis, of the Sackler School for Graduate Biomedical Sciences, leads the NIH-funded Post-baccalaureate Research and Education Program (PREP), designed to provide a bridge from undergraduate to graduate studies by allowing five students a year to "apprentice" in a scientist's laboratory.

The NSF Integrative Graduate Education and Research Traineeship program is an example of a Federal graduate training program that encourages mentorship, career development, hands-on experience with innovation and translating research discoveries to solutions for societal challenges. These best practices should be expanded beyond the frontier interdisciplinary programs that IGERT supports to graduate training across the life and physical sciences and engineering. The NSF REU program accomplishes similar aims with undergraduates. The School of Engineering has received multiple awards to support student research projects during the summer, as well as support from the NIH (ARRA funding), opening students to the possibilities of research.

Programs that support network creation, workshops, travel and summer programs for researchers are useful to raise awareness across scientific communities about science at the interfaces among disciplines. Tufts University has developed a number of ad hoc programs to address this need, including annual Research Days, sponsored by the Office of the Vice Provost. These day-long seminars feature Tufts researchers presenting talks and poster sessions on a particular scientific theme with focus on the various approaches to research on that theme, from molecular biology to drug discovery to clinical trials to policy implications. Similarly, Tufts had its first Science Day, which focused specifically on interdisciplinary research, and featured talks on the barriers to such research, the successes achieved, and strategies for improvement. Both of these initiatives have resulted in new collaborations both within Tufts and between Tufts faculty and industry representatives who attended.

With a relatively modest Federal investment, such programs as these can be expanded beyond a single institution to regional or national conferences that encourage and facilitate a greater understanding of the research conducted and its broader applications and that foster increased collaboration. With "Sabbatical" cross-disciplinary opportunities for post-docs and graduate students, these programs can help to create a community of researchers alert to and equipped to conduct interdisciplinary research, thus resulting in a cultural shift away from disciplinary "silos." The new NSF Science, Engineering, and Education for Sustainability Fellows is an example of a program that supports this type of activity.

Fellowships that allow students to spend part of their graduate careers working in industry or other sectors help create networks between academia and industry, foster real-world learning, and provide students with greater understanding of workforce opportunities beyond the university lab. Collaborative research with industry and orienting research toward grand challenges defined in concert with industry help foster student awareness of industry challenges and skills. The NSF Grant Opportunities for Academic Liaison with Industry (GOALI) program is an example of Federal funding that catalyzes industry student exchanges and research collaborations.

Question 12: What role might government, industry, and academia play in encouraging successful entrepreneurships by faculty, graduate students, and postdocs?

Currently, academic researchers face many challenges when seeking opportunities for entrepreneurship, as discussed earlier. Federal funding in the form of supplements to research grants for commercialization opportunities and programs devoted to entrepreneurship and commercialization (such as NSF's I-Corps, Small Business Administration centers, Department of Commerce activities, and University Centers of Excellence) can help to overcome these barriers. Additionally, providing funds for partnerships with business schools will help to mentor students and postdocs in entrepreneurship and business plan building. These partnerships can further help to demystify the process of licensing technologies or explore business start-up opportunities, and help to create a culture in which these activities are encouraged at all levels of faculty and administration.

Furthermore, to minimize conflicts in intellectual property ownership and protracted negotiations on the value of early stage IP, Federal programs should focus on open innovation, as in models like Pfizer CTI.

Public-Private Partnerships

Question 16: What are the highest impact opportunities for public-private partnerships related to the bioeconomy? What shared goals would these partnerships pursue, which stakeholders might participate, and what mutually reinforcing commitments might they make to support the partnership?

Essentially, the importance of university and non-profit research institution participation in successful public-private partnerships and actively growing innovation ecosystems must be recognized. These public-private partnerships should focus on the development of an active ecosystem, in which the private sector can provide the infrastructure, and the public sector should provide proof of concept funding for new start-ups. To maximize the leverage of Federal dollars, matching programs, in which private and/or state funding is required, can further strengthen these partnerships, and a shared goal of sustained partnerships should be shared by the institution and the public entity.

Question 17: What are the highest impact opportunities for pre-competitive collaboration in the life sciences, and what role should the government play in developing them? What can be learned from existing models for precompetitive collaboration both inside and outside the life-sciences sector? What are the barriers to such collaborations and how might they be removed or overcome?

Barriers to precompetitive collaboration are often highly related to the potential for profits, and to the control of intellectual property. Industry is often hesitant to share technologies or expertise given the need for transparency and open source in many precompetitive efforts. Additionally, industry is highly motivated in speeding regulatory processes, especially with the FDA. Buy-in from the FDA in precompetitive, engineering-based approaches to either continuous manufacturing technologies or personalized medicine is a high-impact opportunity.

Another highly promising approach to pre-competitive collaboration in the life sciences is the integration of scientific disciplines, such as engineering and medicine, in initiatives such as the Koch Institute at MIT, which is focused on engineering and cancer. These multidisciplinary approaches to problems can yield novel therapies and devices, and funding for these types of initiatives should be increased. Furthermore, these initiatives should be developed in such a way as to facilitate innovative collaborations among different disciplines, as well as to include those with expertise in translating findings from the bench to the marketplace.