Testimony of

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INVESTING IN HIGH RISK, HIGH REWARD RESEARCH

Chairman Lipinski, Ranking Member Ehlers, and distinguished members of the Subcommittee on Research and Science Education, thank you for inviting me to participate in this hearing on "Investing in High Risk, High Reward Research."

Mr. Chairman, as you know, the U.S. National Science Foundation (NSF) is first and foremost an innovation agency that has a long history of success in supporting research with far-reaching impacts on the U.S. economy and the well-being of Americans. Since 1950 this success has relied on a close partnership with America's colleges and universities, which are the principal locus of the research NSF funds. NSF research grants are made for the short or long term and its results are public, unlike industry which usually has shorter-term goals aimed at the market place and proprietary results. An NSF hallmark is its continuing effort to advance transformative science by encouraging high risk/high reward research in the context of the structures, programs, and policies needed to function as innovation agency.

Scientific discovery is a social process, a community endeavor that takes time, and is by design cumulative, skeptical, and critical of new results. Transformative discoveries happen because of these qualities (not in spite of them). Moving from an "aha moment" to value creation in a knowledge economy is a complex process involving interactions among people, social structures, and institutional practices and cultures. Research in history, philosophy, and social studies of science teaches us that attempts to predict which individual ideas or projects that are likely to be "transformative" are challenging and imprecise at best.

The challenge for agencies like NSF that fund research done by other organizations is to create and sustain a culture of innovation in which the flow of information among its members creates an institutional culture and framework that stimulates, reinforces, and rewards creativity, and pervades the agency and guides its decision making process.

Creating and sustaining innovation

NSF's decisions are based on the advice of its constituents though merit review, which is a form of what is now called "crowd sourcing" or a way to leverage group collaboration toward the goal of identifying the best research. Most merit review at NSF is done by convening groups of scientific experts, which creates a special institutional role for NSF in the evolution of values in the American scientific community: in this case valuing the importance of potentially transformative ideas and investment in potentially high reward research that has risks.

As we share and discuss transformative science with reviewers, panelists, and advisory committees, they incorporate that idea in their own evaluations and promote it in other scientific venues. Interactions among NSF reviewers, program officers, applicants for research and education funding and awardees have shaped and are shaping the culture of American science. Establishing and sustaining this three-way relationship is a signal contribution of NSF and at the heart of the process of discovery in U.S. science.

The recent Netflix million-dollar prize competition is a compelling example of the successful use of crowd sourcing for technological discovery while also contributing to a culture of innovation. Netflix offered $1 million to anyone who could improve their algorithm for matching movies with customers. The incentive was hugely successful. Of the many creative submissions, two proposed the same promising and highly transformative approach. These two submissions were 20 minutes apart so that under the rules of the contest, the first submission won. However, as described in a recent *New York Times* (September 22, 2009) report by Steve Lohr:

> "..the scientists and engineers on the second-place team, and the employers who gave many of them the time and freedom to compete in the contest, were hardly despairing.
>
> Arnab Gupta, Chief Executive of Opera Solutions…took a small group of his leading researchers off other work for two years. 'We've already had a $10 million dollar payoff from what we've learned,' Mr. Gupta said. 'So for us, the $1 million dollar prize was secondary, almost trivial.'"

By any measure, the outcomes of NSF's investments in frontier research in science, engineering, and science education are impressive. NSF's tradition of merit review that enables new ideas to be tested and funded has served the nation well. The hallmarks of NSF merit review are:

- Review criteria that identify those ideas that will make a difference both in terms of intellectual merit and broader impacts;

- A selection process that combines evaluation by independent expert merit reviewers with the professional scientific experience and judgment of NSF program officers;

- Management of the merit review process by a combination of permanent program officers, who provide institutional memory and experience, and visiting scientist program officers who contribute recent research expertise.

In the May 12, 2008 issue of *The New Yorker*, James Surowiecki (The open secret of success; http://www.newyorker.com/talk/financial/2008/05/12/080512ta_talk_surowiecki) writes about innovation at the Toyota car corporation, which has two elements. First, Toyota turns principles, such as eliminate waste, have parts arrive when needed, fix problems as soon as they arise, into practice better than its competitors. And second, Toyota defines "innovation as an incremental process, in which the goal is not to make huge, sudden leaps but, rather, to make things better on a daily basis….Instead of trying to throw long touchdown passes, as it were, Toyota moves down the field by means of short and steady gains." This leads Surowiecki to conclude: "And so it [this process] rejects the idea that innovation is the province of an elect few; instead it's taken to be an everyday task for which everyone is responsible." Said differently, innovation succeeds in practice when it is “institutionalized,” when it is central to the institution’s culture, and when the institution itself is structured to create and sustain innovative thinking.

Multiple lines of evidence support the conclusion that discovering the very best science to fund is a social process. The results are context dependent, which means that is crucial to create and sustain an institutional culture that is open to transformative ideas since hoped for discoveries are often resisted because ideas are premature. Discoveries are prized because they are often challenged and tough to achieve. Path breaking is hard work, and the decision to follow someone down a new road is not always the obvious thing to do. Making that decision requires experience and often wisdom.

NSF’s Program Officers are at the center of this decision making process; they are the keystone of the agency’s culture of innovation.

The NSF Program Officer’s role in fostering transformative research

NSF relies on the expertise and experience of its permanent and visiting scientist program officers for funding recommendations. After reading proposals, listening to visiting panel reviewers and gleaning advice from external referees it is the program officer who recommends action on a proposal. It is her or his responsibility to integrate all of the information and make a final recommendation based on an understanding of all of the sources. For this reason program officers play a central role in identifying potentially transformative research.

Stewardship and scholarship responsibilities of program officers go beyond merit review responsibilities. These science administrators look for the extraordinary in the proposals they review to create an award portfolio of emerging ideas and outcomes. Beyond the ideas in proposals, new areas for support emerge from a broad and constant set of interactions with the scientific community. As stewards of the nation's investment in research and science education they determine enabling levels and durations of funding, mentor postdoctoral fellows and early career scientists, facilitate national and international connections within and across fields, and engage in outreach to promote broader participation and the education of a new generation of scientists as well as the general workforce.

A culture of creativity at NSF is encouraged by regular exercises in which program officers identify and present exciting and emerging areas for future investment within and across directorates. "Blue Sky projects" not limited by disciplinary boundaries are encouraged. Such exercises help program officers to incorporate risky, transformative, and/or interdisciplinary research and education projects as essential parts of their award portfolios.

As NSF experiments with and develops new methods of review and funding directed at enabling transformative science, program officers will experience even greater demands on their time and attention in order to manage these innovative processes and their anticipated additional workload. The Subcommittee asked for an assessment of "the impact of flat agency operations budgets on Program Officers' ability to identify and support potentially transformative research proposals." As the research enterprise accelerates and becomes more interdisciplinary, the day to day obligations of proposal and award process management are significantly increasing. Time needed for "just thinking" about a problem, interacting with researchers, and imagining creative new ways to find the best research to fund is decreasing. Fostering program officer creativity requires investment of time and money. . Sufficient personnel and infrastructure support, as requested in the President's 2010 Budget, is needed to ensure that NSF remains a 21^{st} century innovation agency.

Supporting institutional creativity through practices and policies

Identifying proposals during the review process that will produce transformative results before the research is conducted and before the scientific community can assimilate the findings is challenging and imprecise at best. However, the Foundation can and does identify proposals that contain potentially transformative research ideas or concepts, and as discussed already is shaping the institution in ways that facilitate the identification of transformative research. Specifically, NSF has:

- Modified the intellectual merit review criterion to include potentially transformative concepts;
- Established an operational definition of transformative research;

- Provided training to new program officers on the importance of supporting potentially transformative as part of a balanced awards portfolio.

Modifying the Intellectual Merit Review criterion. As a result of discussions with the National Science Board and within NSF, a simple but important addition to the NSF Intellectual Merit review criterion was adopted to emphasize to the scientific community and to NSF staff members the importance of potentially transformative research. On September 24, 2007, NSF's Director issued Important Notice No. 130 on transformative research; important notices are sent to presidents of universities and colleges and heads of other NSF awardee organizations. The notice stated that effective October 1, 2007, the NSF Grant Proposal Guide, as well as new funding opportunities issued after that date, would incorporate the following revised Intellectual Merit Criterion—the new wording is underlined:

> ***What is the intellectual merit of the proposed activity?***
>
> *How important is the proposed activity to advancing knowledge and understanding within its own field or across different fields? How well qualified is the proposer (individual or team) to conduct the project? (If appropriate, the reviewer will comment on the quality of prior work.) To what extent does the proposed activity suggest and explore creative, original, or potentially transformative concepts? How well conceived and organized is the proposed activity? Is there sufficient access to resources?*

All proposals received after January 5, 2008, have been reviewed using this revised criterion. Program officers instruct reviewers to pay special attention to those proposals that may include potentially transformative research.

Defining potentially transformative research. The National Science Board (NSB) defined transformative research as "research driven by ideas that have the potential to radically change our understanding of an important existing scientific or engineering concept or leading to the creation of a new paradigm or field of science or engineering. Such research also is characterized by its challenge to current understanding or its pathway to new frontiers." To make the NSB definition operational within the context of NSF's funding programs, the NSF uses the following definition, which builds on the NSB definition with explanatory text and examples:

> *Transformative research involves ideas, discoveries, or tools that radically change our understanding of an important existing scientific or engineering concept or educational practice or leads to the creation of a new paradigm or field of science, engineering, or education. Such research challenges current understanding or provides pathways to new frontiers.*

Transformative research results often do not fit within established models or theories and may initially be unexpected or difficult to interpret; their transformative nature and utility might not be recognized until years later. Characteristics of transformative research are that it:

a. *Challenges conventional wisdom,*
b. *Leads to unexpected insights that enable new techniques or methodologies, or*
c. *Redefines the boundaries of science, engineering, or education.*

NSF Senior Managers, such as Division Directors, discuss concerns about the conservative aspects of peer review with every panel in order to raise consciousness about the importance of risk-taking and creativity in research. Panels are asked to flag high risk/high reward/transformative research.

Training new program officers. To ensure that program officers understand NSF's commitment to supporting high risk/high reward/transformative research, the Foundation developed a training presentation for new program officers. Senior NSF staff members are advisors at each training session. New program officers receive the May, 2007, NSB Report, "Enhancing Support of Transformative Research at the National Science Foundation;" the Foundation's guiding principles in support of transformative research; the Foundation's working definition of transformative research, including examples; and a set of Frequently Asked Questions (and answers) related to potentially transformative research. Finally, NSF's Annual Report to Employees in 2007 provided guidance to all NSF staff members about the critical importance of identifying and supporting potentially transformative research.

While we cannot predict which research investments will invariably produce transformative results, we can create institutional structures and cultures, such as those discussed already, that provide a context for recognizing and supporting projects that have the greatest chance of leading to fundamentally new discoveries. Collectively, these institutional mechanisms constitute the process of discovery for potentially transformative research. But if NSF is to be America's premier "innovation agency," the institution itself must always be looking for novel mechanisms to discover the best research to fund. Here are some ways NSF is exploring this exciting frontier.

New approaches for identifying potentially transformative research

NSF is experimenting with novel mechanisms for developing, reviewing, and funding exploratory and especially creative research. All are new ways to foster NSF's process of discovery.

In January, 2009, NSF announced a new foundation-wide funding mechanism modeled on the Small Grants for Exploratory Research Program. EAGER (Early-concept Grants for Exploratory Research) awards support the initial stages of untested, but potentially transformative research ideas or approaches. The work may be considered especially "high risk-high payoff" in the sense that it involves radically different approaches, applies new expertise, or engages novel disciplinary or interdisciplinary perspectives.

Appendix 1 has a summary of seven targeted NSF programs that support potentially transformative research.

At the Subcommittee's request, activities in the Directorate for Biological Sciences will be reviewed to illustrate how NSF has many features of an innovation agency, and is actively developing structures, programs, and policies needed to function as such an institution.

Biology research and education today increasingly differ from how they were done 10, even 5 years ago. Frontiers are often at disciplinary "edges:" the intersection of biology and computer and information sciences, engineering, geosciences, mathematics, physical sciences, and social sciences. To the extent that it ever did, biology no longer stops at disciplinary margins, but is reflected in interdisciplinary areas such as bioengineering, biogeochemistry, biomathematics, chemical biology, and evolutionary psychology. The Directorate for Biological Sciences is responding to this reality through:

- Joint CAREER panels involving the Directorate for Biological Sciences and the Directorate for Math and Physical Sciences, which have for six years successfully reviewed proposals from young investigators that integrate innovative research and education at the interface of biology and physics.

- A shared program officer between the Directorate for Biological Sciences and the Directorate for Math and Physical Sciences who is charged with identifying and reviewing proposals in the emerging interdisciplinary area of chemical biology. The success of this activity led us to expand this model with the Geosciences Directorate.

- An Integrated Global Systems Science activity will bring together program officers and professional science support staff members from the Directorate for Biological Sciences and the Directorate for Geosciences in an effort to identify and support the best interdisciplinary research needed to address the global challenges we face as a planet.

- The recently released report "Transitions and Tipping Points in Complex Environmental Systems" from NSF's Advisory Committee for Environmental Research and Education warns that "The global footprint of humans is such that we are stressing natural and social systems beyond their capacities. We must address these complex environmental challenges, and mitigate global-scale environmental change--or accept likely all-pervasive disruptions." This challenge requires both interdisciplinary research at the interface of natural and human systems and improved environmental literacy that will enable policymakers both in the U.S. and around the globe to make the informed decisions that will enable us to live sustainably on Earth. A three-year-old Memorandum of Understanding among the Directorates for Biological Sciences, Geosciences, and Social, Behavioral and Economic Sciences to establish Coupled Natural and Human Systems (CNH) as an ongoing cross-directorate program is a successful example of cross-directorate thinking put into action.

- The Directorate for Biological Sciences is exploring the idea of "Fellowships at the Interface," which will provide training and experience at the interface of biology and other scientific disciplines and education. Consideration also is being given to expanding this program (with an additional investment) to include experience for mid-career scientists at the interface of biology and education.

About 18 months ago Malcolm Gladwell argued in an article in *The New Yorker* that ideas are easy to come by; implementing them is hard. Ideas, Gladwell argued, are not precious, but everywhere. He concluded, therefore, "maybe the extraordinary process that we thought necessary for invention--genius, obsession, serendipity, epiphany--wasn't necessary at all." The trick, he felt, was getting together a group of thoughtful, creative people all thinking about how to solve a problem: ("In the Air;" http://www.newyorker.com/reporting/2008/05/12/080512fa_fact_gladwell/?yrail).

The Directorate for Biological Sciences is using three methods to take advantage of this line of reasoning.

- The "Sandpit" is an experiment in real time, interactive peer review to explore novel solutions to existing problems or indentify new areas of research. The Directorate for Biological Sciences, with participation and support from the Directorates for Math and Physical Sciences, Engineering, Social, Behavioral and Economic Sciences, and Computer and Information Sciences and Engineering, sponsored its first sandpit in the area of synthetic biology in conjunction with the United Kingdom's Engineering and Physical Sciences Research Council (EPSRC) in April, 2009. This sandpit produced five interdisciplinary, multi-investigator projects with support from NSF and EPSRC.

- The Directorates for Biological Sciences, Engineering, and Social, Behavioral and Economic Sciences also funded an EAGER proposal that focuses on developing a "prediction market" for synthetic biology. A prediction market is a social networking method used to predict the most likely outcome of an event like a presidential election or next quarter's sales for a business. The principal investigator for this award will use the method to assess where the most creative research investments can be made to advance the area of synthetic biology.

- Synthesis Centers promote the process of collecting and connecting disparate data, concepts, or theories to generate new knowledge or understanding. Beyond its necessity for innovation in basic science, synthesis increasingly contributes to novel and effective solutions for pressing problems, and to the emergence of new ideas or fields of inquiry that would not otherwise exist. Biology Directorate-funded synthesis Centers in conjunction with other NSF Directorates and federal agencies emphasize interdisciplinary research and education in critical areas of the biological, computer, and social sciences. Current centers include: the National Center for Ecological Analysis and Synthesis, the National Evolutionary Synthesis Center, the National Institute for Mathematical and Biological Sciences, and the iPlant Collaborative. These centers advance our understanding by interdisciplinary activities as well as by “getting together a group of thoughtful, creative people all thinking about how to solve a problem.”

Modern cyberinfrastructure can greatly facilitate these ways of identifying the likely places for a commitment to supporting high risk/high reward/transformative research. The social networking manifest in models like crowd sourcing or prediction markets is based on arguments that there is great value in a collective effort focused on uncovering the best sort of research to fund—the so-called “wisdom of the crowd” argument. However, as noted already, NSF’s merit review system is at its root a wisdom-of-the-crowd model. The new extensions of this fundamental model rely on modern computer and information sciences to integrate tens, hundreds, or even, as in the case of the Netflix Prize also discussed earlier, thousands of researchers focused on solving a common problem. These sorts of social networking models are potentially, in an analogy with Clayton Christian's *The Innovator's Dilemma*, a "disruptive technology" when it comes to discovery related to research and education.

But every presumptive innovation carries with it an implicit challenge: How would one know that a novel idea, invention, or method really made a difference? How can we assess any effort at creativity?

The assessment challenge

NSF tends to describe itself in terms of its awards, just as other federal basic research funding agencies. One form of assessment, then, is a review of the narrative summarizing the kinds of research the agency funds.

NSF tracks research outcomes in the form of highlights, which are short descriptions of research and educational outcomes composed by program officers using material provided by principal investigators. Just as for research proposals, merit review can be applied to institutions, and NSF also uses this method. NSF relies on the judgment of external experts to maintain high standards of program management, to provide advice for continuous improvement of NSF performance, and to ensure openness to the research and education community served by the Foundation.

Every NSF program is evaluated by a Committee of Visitors (CoV) every three years. Each CoV submits a detailed report to the appropriate NSF Advisory Committee, which itself is composed of members drawn from the communities NSF supports. All CoV reports are available (http://www.nsf.gov/od/oia/activities/cov/covs.jsp). CoV reviews provide NSF with assessments of the quality and integrity of program operations and program-level technical and managerial matters pertaining to proposal decisions. Each CoV comments on how the results generated by awardees contribute to NSF's mission and strategic outcome goals, including an assessment of the division/program's investments in high risk/high reward/transformative research projects.

The Advisory Committee for GPRA (Government Performance and Results Act) Performance Assessment (AC/GPA) is charged with determining whether NSF has demonstrated "significant achievement" under its strategic outcome goals. This Foundation-wide Advisory Committee has 22 members from outside of NSF drawn from academia, industry, and government. AC/GPA reports to NSF's Director. In its annual evaluation, the committee focuses on program highlights, reports from CoVs, and issues such as transformative research, broadening participation, and societal benefit. The most recent report notes:

> *It is the unanimous judgment of the 2008 Advisory Committee for GPRA Performance Assessment (AC/GPA) that the National Science Foundation successfully met its performance objectives by demonstrating significant achievement for each of the following three long-term, qualitative, strategic outcome goals in its 2006-2011 Strategic Plan:*
>
> - *DISCOVERY: Fostering research that will advance the frontiers of knowledge, emphasizing areas of greatest opportunity and potential benefit and establishing the nation as a global leader in fundamental and transformation science and engineering.*
> - *LEARNING: Cultivating a world-class, broadly inclusive science and engineering workforce, and expand the scientific literacy of all citizens.*
> - *RESEARCH INFRASTRUCTURE: Building the nation's research capability through critical investments in advanced instrumentation, facilities, cyberinfrastructure and experimental tools.*

However, the AC/GPA also took issue with the practice of evaluating NSF's performance using only highlights because they were limiting in several ways:

- Highlights are annually scoped and cannot address long-term outcomes or societal impacts.
- Highlights are written about individual awards or projects, not fields or communities. The relevance of an individual project or result cannot be understood in isolation.
- Highlights do not capture "people outcomes," which are central to NSF's vision.
- Highlights are anecdotal, both in subject matter and in the non-systematic nature of their collection.

At any given time, these assessment mechanisms provide a contemporary case history of how research results from NSF awards relate to the agency's mission and strategic goals. However, the longer term "transformative" impacts of the knowledge and technologies that result from these successful scientific investments—on subsequent scientific research, the economy, and society—are often realized years later. For funding agencies like NSF, identifying proposals during the review process that will produce transformative results before the research is conducted and before the scientific community can assimilate the findings is challenging at best.

Mistakenly, it is sometimes assumed that research discoveries can be quickly brought to market and this rate can serve as an assessment metric. But it is intrinsic to the research enterprise that investments that are scientifically successful in the short term cannot guarantee similar short-term economic gains. Dr. Julia Lane of NSF noted recently that:

> "… [A] focus on economic value alone may also understate the true returns of investments in science. Indeed, one strand of research is attempting to develop a public value mapping of outcomes: outcomes that are public, nonsubstitutable, and oriented to future generations and that capture dimensions such as competitiveness, equity, safety, security, infrastructure and environment." [Assessing the Impact of Science Funding. 2009. Science 324, 1273-1275]

The 2008 AC/GPA recommended that NSF "consider ways to convey the long view of NSF investments in science and engineering" and "track future outcomes from people trained and supported by the Foundation." However, the absence of computer information systems designed to manage information rather than to simply process reviews, awards, or reports is a serious impediment to understanding how NSF awards connect to leading edge science and long-term outcomes. What is needed is a program information management system that connects the agency's award portfolios with one another, with other federal research agencies, with the scientific community, and with the public. Such a system would enable a reciprocal interaction (another form of crowd sourcing) among all of these elements.

The NSTC's Science of Science Policy Interagency Group has identified this lack as a major issue in its recent Roadmap (http://www.ostp.gov/galleries/NSTC%20Reports/39924_PDF%20Proof.pdf). In particular, there are currently no data infrastructure that identifies the universe of individuals funded by federal science agencies (PIs, coPIs, graduate and undergraduate students, lab technicians, science administrators, etc.) and that systematically couples science funding with the outcomes generated by those individuals. In searching for prototypes for the development of more meaningful assessment methods, NSF has begun to look within—to the Directorate for Social, Behavioral and Economic Sciences (SBE), where Program Officers and a research community think about these things—for the methods and measures needed to understand the transformative contributions of new scientific knowledge to economic and social outcomes, to inform future investments, and to convey this information in a manner that is understandable to policy makers and the public. SBE has programs such as Science of Science and Innovation Policy (SciSIP) and Science, Technology and Society (STS) that are funding work on next generation science assessment. Also, SBE's Science Resource Statistics Division, the nation's resource for science statistics, is dedicated to continual improvement through ongoing workshops and consultations.

The role of NSF, universities, and the private sector in supporting potentially transformative research

As noted earlier, NSF has a long history of success in supporting research with far-reaching impacts on the U.S. economy and the well-being of Americans. Since 1950 this success has relied on a close integration with America's colleges and universities, which are the principal locus of the research NSF funds; unlike other federal agencies, NSF has no intramural labs or research staff. Significantly, NSF research grants are made for the short or long term, and results are not classified, but readily published in the open literature. In contrast, industry usually has shorter-term goals aimed at the market place, and results are often proprietary and therefore not readily shared.

In the October, 2008, issue of *Computerworld*, Gary Anthes wrote: "By most measures, the U.S. is in a decade-long decline in global technological competitiveness. The reasons are many and complex, but central among them is the country's retreat from long-term basic research in science and technology, coupled with a surge in R&D by countries such as China." He went on to note that "the kind of pure research that led to the invention of the transistor and the Internet has steadily declined as companies bow to the pressure for quarterly and annual results." He emphasized how many companies now support development, as opposed to the kind of basic research done at colleges and universities with NSF support. And there is also an increasing trend on industry's part to take even the basic research that it does offshore. Thomas Friedman recently noted to his dismay that "America's premier solar equipment maker, Applied Materials, is about to open the world's largest privately funded research facility—in Xian, China." (The New Sputnik. *New York Times*, Sunday, September 27, 2009:p. wk 12.)

If federal agencies such as NSF were to adopt shorter-term perspectives exclusively as a way to meet new national needs, we risk an eventual intellectual and technological vacuum. Anthes feels this is already happening: "The refocus from long-term research to shorter-term development in industry -- and Bell Labs is by no means the only example -- has been mirrored by a similar trend among the Washington agencies that fund science and technology, such as the Departments of Defense and Energy, the National Institutes of Health and the National Science Foundation. Federal funding for R&D has not declined overall -- it has, in fact, increased. But since the early 1990s, funding has been more and more focused on the short-term needs of government." He reports no evidence in support of this claim, but the point deserves reflection.

The U.S. must continue to support transformative research with potential long-term benefits. In a science and technology-based world that will underlie knowledge-based economies to divert our focus from the frontier is to disadvantage us in many ways. Sometimes it just takes unfettered time to make discoveries at the leading edges of knowledge: it is just this freedom that is the essential quality of the R&D that NSF as an innovation agency supports in partnership with America's institutions of higher learning. The NSF activities in Appendix II are examples of the productive intersection between basic research supported by a federal agency and the private sector and universities.

For nearly 60 years NSF has been forward looking in terms of how the agency manages the scientific enterprise. Merit review fosters the "process of discovery," that is the means by which researchers can identify and answer leading/transformative/grand challenge questions. At the heart of the task of being a manager or administrator of the scientific enterprise there should be an abiding interest in the best ways to identify leading/transformative/grand challenge research opportunities. As new modes of science management emerge, especially those facilitated by modern information management systems, science administrators at the frontier will increasingly experiment with these new methods.

Mr. Chairman, as I noted at the start of my testimony, NSF has many features of an innovation agency, and these features will continue to evolve in ways that will ensure NSF’s place as first and foremost an innovation agency dedicated to funding the world’s best research and education.

I appreciate the opportunity to appear before the Subcommittee to speak to you on this important topic. I would be pleased to answer any questions that you may have.

Appendix 1

NSF-targeted activities supporting potentially transformative research

In the Directorate for Engineering (ENG), the **Office of Emerging Frontiers of Research and Innovation (EFRI)** was conceived specifically to support high-risk, high-reward research. Beginning with its first awards in 2007, EFRI has funded investigations in areas where new concepts, new collaborations, and new approaches are essential to address grand engineering challenges or national needs. For example, EFRI researchers are investigating the topic of autonomously reconfigurable systems, which can respond to even unanticipated changes of circumstance. Teams are conducting unprecedented research to forge a theoretical framework for embedding autonomous reconfigurability into any type of complex system, including air traffic, wireless communication networks, and urban transportation networks. One team is creating a group of robots that can sense variables in their surroundings and self-assemble into a structure best suited for that particular environment. Engineering this new capability into human-made systems could transform infrastructure reliability and disaster response.

Since its inception, the **Engineering Research Center (ERC)** program has supported high-risk, transformative research and the development of the nation's leaders in innovation. The 2009 solicitation focuses explicitly on new mechanisms to link discovery to technological innovation in order to concurrently advance technologies and produce engineers who can lead U.S. innovation in a globally competitive economy. Two examples of transformative results from ERC-supported research include the portable defibrillator and early warning systems for tornadoes and other low-ground storm systems.

In the Directorate for Computer & Information Science & Engineering (CISE), the focus in 2010 for transformative research will include the **Expeditions in Computing** Program. Expeditions are large multidisciplinary awards targeted to compelling, transformative research agendas that promise disruptive innovations in computing and information science and engineering. Funded at levels of up to $10 M, Expeditions represent some of the largest single investments currently made by CISE.

The NSF-wide **Cyber-enabled Discovery and Innovation** (CDI) program is another example of NSF's support for potentially transformative research. CDI recognizes that "computational thinking" (i.e., computational methods, concepts, models, algorithms and tools) will transform how all science and engineering will be conducted in the 21st Century. Computational abstractions, as much as high-speed computers and high-bandwidth networks will enable scientists and engineers to make new discoveries by changing the very questions they can ask. Above and beyond the usual NSF requirements, CDI uniquely requires that research projects advance two or more disciplines as well as innovations in or innovative uses of computational thinking.

The NSF Office of Cyberinfrastructure (OCI) will focus investments on the **Strategic Technologies for Cyberinfrastructure (STCI)** Program whose primary purpose is to support work leading to the development and/or demonstration of innovative cyberinfrastructure services for science and engineering research and education that fill gaps left by more targeted funding opportunities. In addition, STCI considers highly innovative cyberinfrastructure education, outreach and training proposals that lie outside the scope of targeted solicitations.

The **Directorate for Social, Behavioral and Economic Sciences (SBE)** is working to catalyze transformative science in three major ways. First, its largest funding opportunities are for multidisciplinary research projects, thus encouraging the transformations that are possible when disciplinary silos are shattered. Second, SBE has alerted its scientists that it is interested in funding complexity science projects. Complexity science lies at the edge of normal science and is especially promising terrain for transformative insights. Third, SBE is working with its communities to identify and create major infrastructure – particularly new databases and new tools for assembling, analyzing and managing data – that will enable next generation analyses of social, behavioral and economic phenomena. SBE has chosen to do all this by integrating these transformative mechanisms into its regular standing scientific programs rather than by creating separate activities. This is because they want to ensure that the appreciation and norms for reviewing and supporting potentially transformative science are visible to and integrated into the entire community, rather than separated from normal scientific review and discussion.

The NSF **Plant Genome Research Program** (PGRP) within the Directorate for Biological Sciences (BIO) began in February 1998 as part of the National Plant Genome Initiative (NPGI), which is managed across federal agencies by an Interagency Working Group on Plant Genomes. The long-term goal of the NPGI is to develop and apply basic plant genome knowledge to a comprehensive understanding of economically important plants and plant processes. Connecting basic research to plant performance in the field accelerates basic discovery and innovation, which enables improved management of agriculture, natural resources, and the environment. To date the PGRP has contributed to the genome sequences and tools for studying both model and crop plants, including Arabidopsis, maize (corn), soybean, potato, tomato and Medicago. Training and outreach is built into all PGRP projects. PGRP-supported tools such as Targeted Induced Local lesions IN Genomes (TILLING) are now used in research and commercial settings for a wide range of plants and animals. TILLING technology has led to a spin-off company that is now part of Arcadia Biosciences. Since agricultural challenges do not stop at national borders, the PGRP, in coordination with USDA and USAID, expanded its efforts in 2004 to include Developing Country Collaborations for Plant Genome Research. In 2009, the NSF in partnership with the Bill & Melinda Gates Foundation (BMGF) established a new program called **Basic Research to Enable Agricultural Development** (BREAD). With equal support from NSF and BMGF (a total of $48 million over 5 years), BREAD will fund basic research to develop innovative solutions to the agricultural problems faced by small farmers in developing countries. This exciting new partnership will enable NSF to leverage basic research advances made through the NPGI with BMGF funding for implementation to international partners. The Plant Genome Research Program has developed tools and resources that not only have transformed our understanding of plant structure and function, but that now are enabling us to tackle pressing needs for new plant-based materials, new energy sources, and plants that adapt to environmental stresses resulting from a changing climate.

Appendix II

Examples of NSF activities at the intersection of federally funded basic research and the private sector and universities

NSF-funded Centers are designed from the outset with built-in flexibility so that investigators can pursue innovative ideas within the context of a defined program of research. Examples are legion, and include the Mosaic web browser developed at NSF's National Center for Supercomputing Applications at the University of Illinois. NSF's creation of two Centers for the Environmental Implications of Nanotechnology (CEIN) in 2008 exemplify innovative networks that are connected to other research organizations, industry, and government agencies to strengthen our nation's commitment to understanding the potential environmental hazards of nanomaterials and to provide basic information leading to the safe environmentally responsible design of future nanomaterials.

The **Industry/University Cooperative Research Centers (I/UCRC)** program develops long-term partnerships among industry, academe, and government. Each I/UCRC contributes to the Nation's research infrastructure, enhances the intellectual capacity of the STEM workforce by integrating research with education, and encourages and fosters international cooperation and collaborative projects. For example, the NSF Industry/University Collaborative Research Center (I/UCRC) known as the Berkeley Sensor and Actuator Center conducts industry-relevant, interdisciplinary research on micro- and nano-scale sensors, moving mechanical elements, microfluidics, materials, and processes that take advantage of progress made in integrated-circuit, bio, and polymer technologies. This I/UCRC has developed and demonstrated a handheld device that allows verified diagnostic assays for several infectious diseases currently presenting significant threats to public health, including dengue, malaria, and HIV. The device uses a dramatically simplified testing protocol that makes it suitable for use by moderately-trained personnel in a point-of-care or home setting. The center has also created many spin-off ventures including companies in the areas of wireless sensor networks for intelligent buildings; MEMS mirror arrays for adaptive optics; and optical flow sensors for industrial, commercial, and medical applications.

The objective of the NSF **Small Business Innovation Research (SBIR)** program is to increase the incentive and opportunity for small firms to undertake cutting-edge research that would have a high potential economic payoff if successful. For example, in 1985, Andrew Viterbi and six colleagues formed "QUALity COMMunications." In 1987–1988 NSF SBIR provided $265,000 (Phase I 8660104 and Phase II 8801254) for single chip implementation of the Viterbi decoder algorithm. Qualcomm introduced CDMA (code division multiple access) which replaced TDMA (time division multiple access) as a cellular communications standard in 1989. This advance led to high-speed data transmission via wireless and satellite. Now the $78B company holds more than 10,100 U.S. patents, licensed to more than 165 companies. Another example - Machine Intelligence Corp. was supported by SBIR Phase I and Phase II awards to develop desktop computer software that could alphabetize words, a feat that previously had been accomplished only on supercomputers. When Machine Intelligence went bankrupt, principal investigator Gary Hendrix founded Symantec and continued the project. The line of research resulted in the first personal computer software that understood English, marketed as "Q&A Software." Q&A quickly became an extremely successful commercial product and remains a widespread commercial application of natural language processing. Symantec research supported by NSF SBIR eventually led to six other commercial products and contributed to 20 others. Now, Symantec is a leading anti-virus and PC-utilities Software Company valued at $12B with more than 17500 employees worldwide.

NSF launched the **Integrative Graduate Education and Traineeship Program (IGERT)** in 1997 to encourage innovative models for graduate education at colleges and universities across the nation that would catalyze a cultural change in graduate education – for students, faculty and institutions. IGERT was designed to challenge narrow disciplinary structures, to facilitate greater diversity in student participation and preparation, and to contribute to the development of a diverse, globally-engaged science and engineering workforce. The result has been a cadre of imaginative and creative young researchers. For example, an NSF-funded IGERT award to the Scripps Institute of Oceanography (NSF #0333444) supported a doctoral student who successfully modeled the extinction of the Caribbean monk seal and demonstrated the magnitude of the impact of over-fishing on Caribbean coral reefs. This research developed improved ecological models, which may influence environmental policy and ultimately lead to the preservation of species and ecosystems for future generations.