



National Science Board

Enhancing Support
of Transformative
Research at the
National Science
Foundation

May 7, 2007



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of Transformative Research
at the National Science Foundation**



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## Task Force on Transformative Research

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May 7, 2007

MEMORANDUM FROM THE CHAIRMAN OF THE NATIONAL SCIENCE BOARD

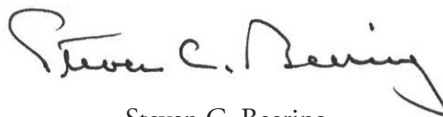
SUBJECT: *Enhancing Support of Transformative Research at the National Science Foundation*

The National Science Board (Board) established the Task Force on Transformative Research (Task Force) in December 2004 to serve as a Board focal point for gaining a better understanding of National Science Foundation (NSF) policies to solicit, identify, and fund innovative, “potentially transformative” research. Transformative research is defined as research driven by ideas that have the potential to radically change our understanding of an important existing scientific or engineering concept or leading to the creation of a new paradigm or field of science or engineering. Such research is also characterized by its challenge to current understanding or its pathway to new frontiers.

The Board, established by Congress in 1950, provides oversight for, and establishes the policies of NSF. It also serves as an independent body of advisors to the President and Congress on national policy issues related to science and engineering research and education.

The Task Force conducted a series of three workshops held in August 2005, December 2005, and May 2006 for Board Members and representatives of key NSF constituent groups to obtain perspectives on the above issues of transformative research. Prior to the establishment of the Task Force, a Board *ad hoc* Task Group on High Risk Research conducted an initial review, which included a workshop in September 2004, of practices that NSF and other organizations in the scientific community used to identify and support transformative research.

*Enhancing Support of Transformative Research at the National Science Foundation* presents the Board’s findings and recommendation for NSF to enhance its ability to identify and fund transformative research. The Board recommends that NSF develop a distinct, NSF-wide Transformative Research Initiative distinguishable by its potential impact on prevailing paradigms and by the potential to create new fields of science, to develop new technologies and open new frontiers. The Board looks forward to having the NSF report back to the Board with a preliminary plan by the August 2007 Board meeting.



Steven C. Beering  
Chairman  
National Science Board

## Acknowledgements

We greatly acknowledge the significant contribution of Dr. Nina Fedoroff, a former Member of the National Science Board (Board), who served as the initial chairman of the Task Force on Transformative Research (Task Force) and led its predecessor group, the *ad hoc* Task Group on High Risk Research (Task Group), until the end of her term of appointment to the Board in May 2006. We also thank former Board Members, Dr. Louis Sequeira, who served on the Task Group in 2004; Dr. Daniel Simberloff, who served on the Task Force and Task Group in 2004; and current Board Member, Dr. Kenneth Ford, who served on the Task Force from 2004 to 2006.

We are grateful to the many individuals from the science and engineering community who generously contributed their time and intellect to the development of this Board report. Listings of the participants and speakers in the four Board-sponsored workshops for the Task Force and Task Group are included on the Board's Web site, <http://www.nsf.gov/nsb/committees/tr/index.htm>. We particularly appreciate the endeavors of external core participants, Dr. Donald Braben, Venture Research International; Dr. Irwin Feller, American Association for the Advancement of Science; Dr. Gerald Pollack, University of Washington; and Dr. Keith Yamamoto, University of California, San Francisco.

The Board also thanks the many National Science Foundation staff members who contributed to this undertaking, especially Dr. Arthur Ellis (now with University of California, San Diego) and Dr. Nathaniel Pitts, who served as NSF liaisons to the Task Force.

Finally, our Board Office staff, led by Dr. Michael Crosby, the Board's Executive Officer and Board Office Director, provided essential support and valuable contribution throughout this effort. Especially deserving of recognition are Ms. Ann Ferrante, Executive Secretary for the Task Force, Board Office; Ms. Amanda Slocum, former Board Science and Engineering Policy Assistant (now with Carnegie Mellon University); and Ms. Melody Kroll, Editorial Assistant to Dr. Douglas Randall.

# Enhancing Support of Transformative Research at the National Science Foundation

## Introduction and Overview

*The National Science Foundation must support the most innovative and potentially transformative research—research that has the capacity to revolutionize existing fields, create new subfields, cause paradigm shifts, support discovery, and lead to radically new technologies... The Foundation must create an environment that is more open to and encourages transformative research proposals from the research community.*

NATIONAL SCIENCE BOARD, 2020 VISION FOR THE NATIONAL SCIENCE FOUNDATION, 2005

## Introduction

Science progresses in two fundamental and equally valuable ways. The vast majority of scientific understanding advances incrementally, with new projects building upon the results of previous studies or testing long-standing hypotheses and theories. This progress is evolutionary—it extends or shifts prevailing paradigms over time. The vast majority of research conducted in scientific laboratories around the world fuels this form of innovative scientific progress. Less frequently, scientific understanding advances dramatically, through the application of radically different approaches or interpretations that result in the creation of new paradigms or new scientific fields. This progress is revolutionary, for it transforms science by overthrowing entrenched paradigms and generating new ones. The research that comprises this latter form of scientific progress, here termed *transformative research*, is the focus of this report.

In practice, distinguishing between innovative and transformative research is difficult at best and, some would argue, only possible in hindsight. Indeed, the two forms of scientific progress do exist side-by-side and, often, proceed hand-in-hand and overlap each other. For example, Alfred Wegener's theory of continental drift, which significantly transformed concepts of our world, required decades of innovative research to prove its validity. Undoubtedly, there are many pathways to transformative breakthroughs. This report, however, is interested in a particular pathway—in our view, the one less traveled. This pathway is marked by its challenges to prevailing scientific orthodoxies. Albert Einstein, Barbara McClintock, and Charles Townes are just three modern examples of scientists who chose this path. Their discoveries, and many others,<sup>1</sup> not only fundamentally transformed science and engineering, but also shaped the quality of our lives by paving the way for new frontiers and new technologies in industry, in commerce, and in national security. Although defining such breakthroughs *a priori* is difficult, attempts to do so are not in vain because history unequivocally records the essential benefits to mankind.

Truly revolutionary advances in science today may need particular nurturing, especially at the proposal stage. Recently, two reports articulated a concern about the current decline in support of research. In its 2005 report *Assessment of Department of Defense Basic Research*, the National Research Council found a general decline in support of basic research over the past



decade as well as a recent de-emphasis on “unfettered exploration, which historically has been a critical enabler of the most important breakthroughs in military capabilities.”<sup>2</sup> Similarly, in its “roadmap” for medical research in the 21st century, the National Institutes of Health also recognized a need to stimulate “high-risk/high-impact” medical research with the potential to result in groundbreaking discoveries.<sup>3</sup>

The underlying concern of these reports and, indeed, of this one is that failure to encourage and to support revolutionary ideas will jeopardize not only our Nation’s ability to compete in today’s and tomorrow’s global economy, but also the progress of science as a whole. This concern is articulated best in the much publicized and widely heralded 2005 report from The National Academies *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*.<sup>4</sup> The authors identify factors that contribute to the United States’ eroding competitiveness in the global economy; the recent decline in support of “high-risk or transformative research,” particularly in the physical sciences, engineering, mathematics, and information sciences is identified as one major factor. The authors state that “reducing the risk for individual research projects *increases* the likelihood that breakthrough, ‘disruptive’ technologies will not be found—the kinds of discoveries that yield huge returns.”<sup>5</sup> As testimony to both the strength and the urgency of the report’s findings and recommendations, President George W. Bush, in his 2006 State of the Union Address, announced the American Competitiveness Initiative in order to encourage greater scientific innovation and to strengthen the United States’ ability to compete in the global economy. A leading component of the President’s comprehensive strategy is the support of “groundbreaking ideas generated by innovative minds” through a doubling of the Federal commitment to the most critical basic research programs in the physical sciences during the next 10 years.<sup>6</sup>

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“Although basic research that has the potential to be transformational is inherently less predictable in its course and eventual outcomes, it is, nonetheless, absolutely essential for our national advancement and for the advancement of science as a whole.”

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Although basic research that has the potential to be transformational is inherently less predictable in its course and eventual outcomes, it is, nonetheless, absolutely essential for our national advancement and for the advancement of science as a whole. How the National Science Foundation (NSF, Foundation) can enhance the solicitation and support of such research is the focus of this report.<sup>7</sup>

## History and Structure of the Report

Congress established the National Science Board (Board) in 1950 and gave it dual statutory responsibilities: to provide oversight for, and establish the policies of NSF, and to serve as an independent body of advisors to both the President and Congress on broad national policy issues related to science and engineering research and education. Examining NSF’s support of scientific research and making recommendations for improvement fall within the purview of the Board’s mandate.

While the substance of this report is drawn primarily from work conducted over the last 2 years, NSF’s support of transformative research has been articulated as a Board priority as early as July 1999 (NSB-00-39).<sup>8</sup> Later, in comments made to the Committee on Science, House of Representatives Subcommittee on Basic Research on October 4, 2000, Eamon Kelly, former Chairman of the Board, noted that “industry is increasingly dependent on the Federal government to support long-term and high-risk research at the same time that the Federal share of the U.S. [research and development] enterprise is declining.”<sup>9</sup> In 2003, Board Members discussed ways in which the Foundation’s management could develop new and more effective approaches to encourage, to evaluate, and to fund research that has the potential to transform disciplines. Meanwhile, NSF asked the Advisory Committee on Government Performance and Results Act (GPR) Performance Assessment (AC/GPA)

to comment on the Foundation's support of "transformative/ bold /innovative-high risk research and education."<sup>10</sup> Although the committee concluded that no obvious formula exists to guide NSF as to the fraction of the portfolio that should be "high risk" or "bold," it did suggest that "NSF should do more," stating that "advancing the frontiers of human knowledge requires, indeed demands, that our research portfolio contain investments with long odds of success but, if successful, with the ability to fundamentally transform our understanding."<sup>11</sup> The committee concluded by stating that this issue is important enough to warrant attention by the Board.

In response to the AC/GPA and the Board's own interest, the Board assembled an *ad hoc* Task Group on High Risk Research to determine whether an assessment of NSF's support of transformative research was warranted. In seeking an answer, the Task Group organized a workshop to solicit a range of views on NSF's effectiveness at supporting transformative research (initially designated "high-risk research").<sup>12</sup> Based upon outcomes from this workshop, the Task Group concluded that opportunities to identify and fund transformative research may be inadvertently missed at NSF and that a formal assessment was warranted.

Consequently, in December 2004, the Board appointed a Task Force on Transformative Research (hereafter, Task Force).<sup>13,14</sup> Its mandate was to serve as a Board focal point for gaining a better understanding of NSF policies aimed at soliciting, identifying, and funding transformative research, to evaluate the effectiveness of these policies, and to suggest possible modifications for the Board's consideration. This report presents the Board's findings and recommendation for how NSF can enhance its ability to identify and to fund transformative research.

## Findings

The Board sought to gain a better understanding of NSF policies aimed at soliciting, identifying, and funding transformative research, to evaluate their effectiveness, and to identify possible modifications to these policies. The Board undertook a review of existing NSF programs intended to fund transformative research, initiated a series of workshops to explore the issues surrounding the Foundation's support of transformative research, and solicited suggestions on how such research could best be supported.<sup>15</sup> Additional information materials and summaries of these activities may be found at <http://www.nsf.gov/nsb/committees/tr/index.htm>. Workshop participants included current and former NSF staff, members of the academic community, individuals with research experience in science metrics and evaluation, and representatives of industry, foundations, and other governmental funding agencies. The key findings of the Board are summarized below.

- ***NSF's ability to solicit, to identify, and to fund transformative research requires a clear definition of transformative research.***

The precise meaning of the phrase "transformative research" has been debated at the Foundation and elsewhere during the past several years. The history of this discourse at NSF is documented in the 2004, 2005, and 2006 reports of the AC/GPA.<sup>16</sup> Although NSF has made an effort to clarify this term, it has not yet established a clear, concise, agency-wide operational definition.

Establishing an operational definition is complicated by the fact that most examples of transformative research are identified as such only long after the work has been completed. Yet, this has not prevented many current NSF programs from using the term "transformative research" in their program announcements. The Directorate for Computer and Information

Science and Engineering and the Directorate for Engineering are the most likely to use this term, although the Directorates for Biological Sciences and Mathematical and Physical Sciences are much less likely. However, use of the term “transformative research” appears to reflect how solicitations are written rather than the nature of the research supported by each directorate. The term also appears to be used synonymously with other terms, including “innovative,” “high risk,” and “bold.”

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“...the Board believes that it is imperative for the Foundation to establish a single, uniform definition of transformative research to highlight its uniqueness and to alert the community that the Foundation invites and supports such research.”

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The failure to establish a formal operational definition and the vague use of the term with differing interpretations across directorates has led to confusion among NSF’s constituent community and NSF management and staff. In its 2005 report, the AC/GPA also noted that this lack of a concise definition makes difficult an accurate assessment of NSF’s ability to identify and to fund such projects.<sup>17</sup> Therefore, the Board believes that it is imperative for the Foundation to establish a single, uniform definition of transformative research to highlight its uniqueness and to alert the community that the Foundation invites and supports such research.

- ***Transformative research frequently does not fit comfortably within the scope of project-focused, innovative, step-by-step research or even major centers, nor does it tend to fare well wherever a review system is dominated by experts highly invested in current paradigms or during times of especially limited budgets that promote aversion to risk.***

The *Report of the National Science Board on the National Science Foundation’s Merit Review System* concludes that “the Foundation’s merit review system remains an international ‘gold standard’ for review of science and engineering research proposals.”<sup>18</sup> Still, the Board finds that investigators are reluctant to submit radical or paradigm-challenging research ideas to NSF given the low conventional success rate (over \$2 billion of highly rated proposals were declined in FY 2004).<sup>19</sup> These unsubmitted proposals are critical missed opportunities.

By its very nature, transformative research often is challenging to and frequently crosses disciplines. It questions the status quo by proposing new (sometimes radically new) ways of approaching a fundamental scientific question (see, for example, the case of Charles Townes, next page). Experts in the areas being challenged (many of whom may sit on review panels) may dismiss such ideas by pronouncing the research overreaching or without basis. Consequently, such ideas can remain hidden or discouraged and their breakthrough discoveries delayed or even missed.

It is important to recognize that mechanisms exist within NSF to ensure that proposals not recommended for funding by reviewers are considered. For example, Program Officers are not required to recommend awards based solely on the average numerical rating of reviewers. In addition to considering a panel’s recommendations and reviewers’ comments, Program Officers do consider additional factors, including “the potential for significant impact in the field.”<sup>20</sup> With such freedom and authority, NSF management can and does fund projects with mixed reviews and decline projects with favorable reviews. Finally, NSF also is able to fund projects outside the normal merit-review system through the use of Small Grants for Exploratory Research (SGER) awards. These agency-wide awards were established specifically to support preliminary work on untested and novel ideas, ventures into emerging research, and critical research questions that arise unexpectedly.

Although these mechanisms do exist, the Board concludes that they alone are not adequate to ensure that transformative research proposals are solicited, evaluated, and funded. First and foremost, these mechanisms assume that transformative research is being proposed to NSF.

## Charles Townes and the Laser

“Charles Townes got his PhD in physics at the California Institute of Technology in 1939, and went on to join the Bell Labs, then located in Greenwich Village on Manhattan Island. Soon after, Bell asked him to help develop radar bomb-aiming systems as part of the U.S. war effort. This intense work on radar and microwaves, as he describes it, led him to his career’s work on molecular spectroscopy. Similar war work had been done at the nearby Columbia University in New York, so when Bell Labs suggested that he focus his work on subjects of interest to the company, he decided in 1948 that he would pursue his own interests, and accept an appointment as associate professor of physics at Columbia.

For some time, he had been trying to make intense beams of sub-millimeter radiation, rather than the centimeter or more wavelengths he had been working with. Eventually, he conceived a possible method to generate photon ‘avalanches’ using excited ammonium molecules. But he couldn’t get it to work! As he relates in his book\*:

‘(After) we had been at it for two years, Rabi and Kusch, the former and current chairman of the department—both of them Nobel laureates for work with atomic and molecular beams, and both with a lot of weight behind their opinions—came into my office and sat down. They were worried. Their research depended on the support from the same source as did mine. ‘Look,’ they said, ‘you should stop the work you are doing. It isn’t going to work. You know it’s not going to work. We know it’s not going to work. You’re just wasting money. Just stop!’

But Townes had tenure, so he knew he couldn’t be fired for incompetence or ordered around. Nevertheless, the top-brass are not to be defied lightly, and showing extraordinary courage, this junior faculty member stood his ground, and respectfully told his exalted colleagues that he would continue. Two months later (in April 1954), his experiment worked, and the maser (microwave amplification by stimulated emission of radiation) was born. Three years after that, Arthur Schawlow, Townes’ post doc at Columbia, had moved to Bell Labs, their collaboration led to the optical version of the maser—the laser.

Townes was awarded the Nobel Prize for Physics in 1964 for these discoveries (shared with Alexander Prokhorov and Nikolai Basov (U.S.S.R.) who developed the maser and laser independently).”

\*Charles H Townes, *How the Laser Happened*, Oxford University Press, 1999, p. 65.

Excerpt from forthcoming book by Donald W. Braben, *Mismanagement by Objectives: Its Ruinous Effects on Exploratory Research and What We Must Do to Avoid Collapse*. Used with permission of Donald W. Braben, Venture Research International.

A recurring point made to the Board was that many paradigm-challenging ideas are simply not submitted to NSF. Second, transformative ideas are often fragile in their early stages and often can be multidisciplinary, thus requiring extra time by a Program Officer to negotiate possible joint funding among allied programs. Given the sheer number of research proposals processed by the Foundation every year (there has been an almost 50 percent increase in proposal numbers since 2001 and almost no increase in NSF administrative capacity<sup>21</sup>) and the growth of administrative reporting requirements since implementation of GPRA, there simply is insufficient time for a Program Officer to facilitate (let alone, solicit) all transformative proposals. Third, although each NSF directorate may expend up to 5 percent of its program funds (\$590 million) on such research through SGER awards, only 0.5 percent of such funds (\$29.5 million) were so expended in FY 2004. This underutilization of SGER awards was noted as a concern in the *Report of the National Science Board on the National Science Foundation's Merit Review System*<sup>22</sup> as well as in the AC/GPA performance assessment reports for 2005<sup>23</sup> and 2006.<sup>24</sup>

If transformative proposals do not fare as well as they should within the current proposal review and funding system, under what context and system would they do better? The Board posed this question to representatives of several leading foundations and companies that explicitly seek out transformative research.<sup>25</sup> They shared that their evaluation procedures focus as much (if not more) on the quality and training of the individuals selected as on the proposed project. For example, the Fellows Program of the John D. and Catherine T. MacArthur Foundation seeks exceptional individuals who have a unique worldview and are dedicated to pursuing their own creative vision. The program uses a network of nominators to identify such individuals, but nominations are confidential and there is no direct application or interview process. Similarly, The James S. McDonnell Foundation seeks to identify researchers who question prevailing assumptions in a given field through workshops structured specifically around such issues. They identify individuals or small groups to write proposals, which are then reviewed and refined by expert advisers working together with the investigators. None of the foundations or companies relied solely on peer-review mechanisms to evaluate transformative research. However, these approaches generate their own set of concerns. The Board concludes that a variety of approaches to the selection process might be evaluated to develop new pathways to stimulate proposals for transformative research that might not be currently submitted. The key is to identify individuals or teams with transformative ideas, to encourage them to submit proposals, and to nurture them through the process.

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- ***There exists a substantial external perception that NSF does not support transformative research.***

The Board finds a significant gap between internal and external perceptions of NSF policies and practices with respect to transformative research. Although NSF management espouses an openness to transformative research ideas, most investigators interviewed by the Board perceive NSF as inimical to proposals that challenge current paradigms and approaches. However, the research community itself plays a role in this perception as part of the review process. Consequently, two important and related issues must be considered: (1) the extent to which NSF, as an agency with certain policies and practices, is philosophically supportive and programmatically capable of identifying and supporting transformative research and (2) the extent to which the research community is supportive of such research both in formulating but especially in reviewing proposals. The chief factors contributing to these divergent perceptions are assessed below.

From the Foundation's perspective (and to its credit), much thought has been devoted to devising approaches that identify and fund transformative research at NSF. According to a

review of NSF programs conducted by the Board's Task Force, the Foundation currently has a variety of initiatives that purport to facilitate and support transformative research. These include NSF-wide initiatives such as SGER awards, accomplishment-based renewals, grant extensions,<sup>26</sup> and preliminary proposals; multidisciplinary, multi-directorate initiatives such as those encompassed by the NSF high-priority research areas;<sup>27</sup> large-scale, center-based programs<sup>28</sup> such as the Science and Technology Centers,<sup>29</sup> the Engineering Research Centers, and the Chemical Bonding Centers; large projects such as the Laser Interferometer Gravitational-Wave Observatory and world-class telescopes such as Gemini and Atacama Large Millimeter Array; and organizational structures that attempt to institutionalize cross-directorate or interdisciplinary programs, such as the Frontiers in Integrative Biological Research program located in the Emerging Frontiers Division in the Directorate for Biological Sciences.<sup>30</sup>

In addition, other NSF programs, although not explicitly focusing on transformative research, have the ability to produce transformative outcomes. For example, Small Business Innovation Research, Small Business Technology Transfer, and other initiatives within the Directorate for Engineering's Industrial Innovation and Partnerships Division (IIP)<sup>31</sup> and Civil, Mechanical and Manufacturing Innovation Division (CMMI)<sup>32</sup> involve innovative university-industry collaborations and are often mentioned in NSF discussions of experimental or innovative research. Of all these mechanisms, SGER awards are specifically designed to fund research characterized as preliminary or applied to untested and novel ideas, ventures into emerging research ideas, and the application of new expertise or new approaches to established research topics.

However, from the community's perspective, it is possible to draw the opposite conclusion about NSF's openness to transformative research. Although the aforementioned NSF initiatives for attracting proposals are worthwhile, none are *specifically* dedicated to considering transformative research. Science and Technology Centers and Engineering Research Centers do pursue bold ideas, but they have become increasingly prescriptive and constraining. Although only SGER has the desired flexibility and message, it is both underutilized and often used for purposes other than the support of transformative research (e.g., to support research questions that arise immediately following natural disasters).<sup>33</sup> The reasons for this underutilization are unclear, but could include the short funding period (2 years maximum), the budget limit (only recently increased to \$200,000 total) of SGER awards,<sup>34</sup> the lack of transformative research proposals submitted under this program, and the pressure of so many highly rated but unfunded proposals. NSF is currently evaluating the SGER mechanism and portfolio to determine whether SGER is effective as a mechanism for nurturing transformative ideas.

Additionally, the Board finds that NSF is viewed by much of the research community as having a reputation of funding science that has predictable productivity or opportunity for success. This reputation by the research community appears to be based both on hearsay (scientists telling other scientists that high-risk proposals are "dead upon arrival") and on actual experiences (repeated rejection of such research proposals and the low overall conventional funding rate). The Board believes that the biggest impact of such a reputation is that many researchers are unlikely to submit (or resubmit) paradigm-challenging ideas to NSF.

Notably, a renewed emphasis is being placed on high-risk research at NSF. In a speech at the thirtieth Annual American Association for the Advancement of Science's "Forum on Science and Technology Policy" in 2005, NSF Director, Arden Bement discussed the importance of "frontier science" to the mission of NSF, a reference to Vannevar Bush's highly acclaimed *Science—The Endless Frontier*, which became the basis for the establishment of

the Foundation in 1950. As Bement noted, “Our primary task must be to tenaciously dog the frontier. The frontier is our bull’s eye.”<sup>35</sup> Bement specifically characterized the frontier as inherently “risky,” further stating that “if it’s ‘safe science,’ NSF should not fund it. The frontier is murky and without definition, so if there are no big unanswered questions in a proposal, NSF should pass it up.” In addition to these public statements in support of high-risk research, several Program Officers presented evidence to the Board’s Task Force suggesting an enhanced effort to identify and support “transformative research” in recent years. This trend also was noted by the AC/GPA in its most recent 2006 report.<sup>36</sup> Yet, in both cases, the basis for classifying the proposed research as “transformative” was unclear.

## Conclusions

Although the clear intent of NSF is to support more research that is transformational and that challenges current paradigms, it is the Board’s conclusion that NSF’s messages and mechanisms (as currently structured) will not counteract the external perception by many that NSF is not as welcoming as it should be to such research. This perception is the fundamental bottleneck that NSF faces in enhancing its support of transformative research and that actions are warranted to alter this perception.

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“...the Board recommends a new, distinct, and separate Foundation-wide program designed specifically to solicit and to support transformational and paradigm-challenging proposals.”

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NSF’s current merit-review system is, as noted earlier, the “international ‘gold standard’” for the review and funding of innovative research and its fundamental procedures are sound. Consequently, the Board does not see a need to adjust or to modify the current merit-review mechanism at NSF. Rather, the Board recommends a new, distinct, and separate Foundation-wide program designed specifically to solicit and to support transformational and paradigm-challenging proposals. A separate program would send a clear message to scientists that NSF will consider and support risky and challenging ideas. It also will open up an alternative, non-programmatic and non-discipline-specific path at NSF through which such ideas can be heard and considered. Such an alternative path is necessary in order to overcome the tendency of such proposals to be sidelined by established orthodoxy and limited budgets.

Based on the Board’s analysis, this new program designed to support such research would include the following characteristics:

- a clear, concise definition of “transformative research;”
- an appropriate review and funding mechanisms that can cross traditional organizational boundaries;
- awards sufficient in amount and duration to sustain and accomplish the work;
- engage the entire Foundation;
- have the option of being an individual investigator or multi-investigator effort;
- prestigious (endorsed by the Director’s Office) and developed into a core value of the Foundation;
- support for symposia and other venues that enable and encourage discussion of paradigm challenges;
- emphasis on well-articulated and novel ideas that are scientifically feasible (rather than results obtained to date);
- minimal administrative structure and programmatic constraints (e.g., formal education programs, frequent site visits, strategic plans);
- emphasis on partner-based relationship between principal investigator and program officer; and
- unrestricted as to discipline.

To judge the impact of cultural and programmatic changes that foster transformative research, it is necessary to devise means of measuring success. At present, NSF’s support for transformative research is described anecdotally by citing individuals funded by NSF during their careers who have received prestigious recognition for transformative research, such as a Nobel Prize. If NSF were to implement a new transformative research initiative, it would need to be viewed as an experiment and thus assessed appropriately. Measuring scientific creativity presents a difficult challenge; assessing the difference in outcomes between individuals selected for funding by different mechanisms will be twice as difficult. Although many suggestions for assessing such outcomes were considered, the Board concludes that it is premature to recommend any assessment methodologies.

## Recommendation

For over 50 years, the Foundation has fulfilled its mission of promoting the progress of science by maintaining a diverse portfolio of research investment across a broad array of fields comprising contemporary science and engineering. As a result, the Foundation has been at the forefront of discovery, supporting more than 100 Nobel Prize winners and thousands of distinguished scientists and engineers who have conducted their groundbreaking research with funding from the NSF. Motivated to sustain this type of success at a time of increasing global competition, the Board gave the following as its 2020 Vision for the Foundation:

*The National Science Foundation ensures that the Nation maintains a position of eminence in global science, technology, and knowledge development through leadership in transformational research and excellence in science education, thus driving economic vitality, an improved quality of life, and national security.*

The Board went on to state that to achieve this vision, the NSF will focus on three strategic priorities, of which ensuring the Nation remains “at the global frontier of basic and transformational research” was the first priority.

The Board believes that it is unreasonable to expect that small adjustments to NSF’s existing programs and processes will overcome the perception among much of the external scientific community that iconoclastic ideas are not welcome at NSF. System-wide changes for this purpose are also inappropriate. As noted in the *Report of the National Science Board on the National Science Foundation’s Merit Review System*, NSF’s current merit-review system is functioning effectively to support the excellent innovative research that is significantly advancing the frontiers of knowledge and the goals of our Nation. Nonetheless, our Nation cannot afford to miss opportunities, discoveries, and new frontiers that can result from bold, unfettered exploration and freedom of thought that challenges our current understanding of natural processes. NSF cannot allow the perception by any of the Nation’s scientists that it does not welcome or support their ideas and aspirations. Public support of and careful investment in paradigm-challenging ideas are critical not only to continued economic growth, but also to the future welfare of our Nation. Therefore, the Board makes the following recommendation:

**That NSF develop a distinct, Foundation-wide Transformative Research Initiative (TRI) distinguishable by its potential impact on prevailing paradigms and by the potential to create new fields of science, to develop new technologies, and to open new frontiers.**

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“...our Nation cannot afford to miss opportunities, discoveries, and new frontiers that can result from bold, unfettered exploration and freedom of thought that challenges our current understanding of natural processes.”

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Rationale: This Foundation-wide TRI is intended to attract proposals that meaningfully challenge prevailing paradigms and that have the potential to create new fields of science or



engineering, develop new technologies, and open new frontiers. A separate and Foundation-wide Initiative will provide a clear indication to the entire scientific and engineering community that NSF welcomes, encourages, and supports research ideas that push the frontiers or challenge current orthodoxies. Furthermore, such an initiative will allow investigators (i.e., not NSF or reviewers) to make the initial determination that their proposal is transformational and will open an alternative path for these investigators to proceed along with their proposals, irrespective of their discipline. The Board believes that that this proposed Initiative will seed new scientific revolutions and will provide for open discussion of current paradigm challenges and scientific controversies. This Initiative is meant to be only the first step toward achieving a broader and longer-term capacity for supporting revolutionary ideas within NSF and, more importantly, toward providing the freedom that encourages greater boldness of ideas and aspirations within the research community. (Foundation-wide initiatives have proven highly successful for the Foundation. Examples include Cyberinfrastructure, Global Change, Biocomplexity, and Science & Technology Centers.)

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**The Board asks the Foundation to develop a simple and transparent process for instituting the TRI that encourages maximum participation by the community and appropriate methods for evaluating impact. NSF is to report back to the Board with a preliminary plan by the August 2007 Board meeting.**

The Board offers the following principles for the Foundation to consider during the process:

**1. Adopt the following definition of transformative research.**

*Transformative research is defined as research driven by ideas that have the potential to radically change our understanding of an important existing scientific 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.*

It is critical that the NSF be clear about how it defines and uses the term transformative research. The definition proposed above captures the notion that transformative research is revolutionary. The recommended Foundation-wide TRI and definition of transformative research minimizes ambiguity and highlights this initiative.

**2. The NSF Director’s leadership is essential to this Transformative Research Initiative.**

Involvement of the NSF Director in the proposed program will indicate clearly and unequivocally the high level of importance of paradigm challenges to NSF’s mission. The Board suggests that the Office of the Director lead the effort of weaving the recommended TRI into the core values of the Foundation.

**3. Fund this Foundation-wide Transformative Research Initiative as soon as possible.**

The Board recognizes that NSF has submitted its FY 2008 budget request and that NSF is already unable to fund a significant number of highly rated research proposals. Yet, to show the credibility, prestige, and distinctiveness of this initiative to the research community, to the President, and to Congress, the Board suggests the Foundation develop a means to initiate this program in FY 2008. The Board does not recommend a specific percentage or amount of NSF budget that should be applied to this Initiative, but it should be significant. The Board strongly encourages NSF to fund such awards in sufficient amount and duration as to sustain the often extended gestation period of transformative ideas. The Board believes that most of the successful efforts eventually will meld into the other Foundation programs or may create whole new program areas.

## Endnotes

<sup>1</sup> Other transformative researchers include Ernest Rutherford, founder of nuclear physics; Paul Dirac, founder of the field of quantum physics; Wolfgang Pauli, who discovered the Exclusion principle and predicted the existence of neutrinos; Erwin Schrödinger, founder of wave mechanics; Werner Heisenberg, founder of quantum mechanics; Enrico Fermi, who built the first nuclear reactor; Oswald Avery, who discovered that DNA is a genetic molecule; Linus Pauling, who described the nature of chemical bonds; Max Perutz, who discovered the structure of haemoglobin; Charles Hard Townes, who discovered the maser; and Sydney Brenner, who pioneered the field of molecular biology.

<sup>2</sup> National Research Council. *Assessment of Department of Defense Basic Research*. (Washington, DC: National Academies Press, 2005), p. 3.

<sup>3</sup> See *NIH Roadmap for Medical Research: High-risk Research* at: <http://nihroadmap.nih.gov/highrisk>. See also NIH Director's New Innovator Award. Available at: [http://grants.nih.gov/grants/new\\_investigators/innovator\\_award](http://grants.nih.gov/grants/new_investigators/innovator_award).

<sup>4</sup> Committee on Prospering the Global Economy of the 21st Century: An Agenda for American Science and Technology. Committee on Science, Engineering, and Public Policy, *Rising Above the Gathering Storm: Energizing and Employing American for a Brighter Economic Future* (Washington, DC: National Academies Press, 2006).

<sup>5</sup> *Ibid.*, 1-9 (emphasis theirs).

<sup>6</sup> *State of the Union: American Competitiveness Initiative* (Press Release). January 31, 2006. Available online at: <http://www.whitehouse.gov/news/releases/2006/01/20060131-5.html>.

<sup>7</sup> For a description of NSF current efforts addressing Transformative Research needs, see National Science Board, *Report to the National Science Board on the National Science Foundation's Merit Review Process, Fiscal Year 2006* (NSB-07-22). Available online at: [http://www.nsf.gov/nsb/documents/2007/2006\\_merit\\_review.pdf](http://www.nsf.gov/nsb/documents/2007/2006_merit_review.pdf).

<sup>8</sup> National Science Board, Approved Minutes, Open Session, February 2-3, 2000 (NSB-00-39), unnumbered. Available at: <http://www.nsf.gov/nsb/meetings/2000/feb/nsb0039/nsb0039.htm>.

<sup>9</sup> See *Statement by Dr. Eamon M. Kelly, Chairman, National Science Board, before the Committee on Science, U.S. House of Representatives, Subcommittee on Basic Research*, (October 4, 2000). Available online at: <http://www.nsf.gov/nsb/documents/2000/speeches/kelly10400.txt>.

<sup>10</sup> The AC/GPA is an external, expert review panel that provides a non-quantitative assessment of the Foundation's progress toward achieving its strategic goals. For more information, see <http://www.nsf.gov/about/performance/>.

<sup>11</sup> Noonan, N. E., *Report of the Advisory Committee for the GPRA Performance Assessment: FY 2004* (Washington, DC: NSF, 2004), p. 14. Available online at: <http://www.nsf.gov/pubs/2004/nsf04216/nsf04216.pdf>.

<sup>12</sup> The workshop, titled "Identifying, reviewing and funding transformative research," was held on September 22-23, 2004 at the Santa Fe Institute in Santa Fe, New Mexico. Participants were external researchers from many disciplines and institutions and at different stages in their careers, as well as individuals with experience in industry, other federal agencies, non-governmental organizations, and NSF. The Board Office prepared a background paper to familiarize participants with current NSF programs that purported to target and support high-risk research. Participants also were invited to submit brief written summaries of their views on how well NSF's current practices identify and support transformative research. For more information: <http://www.nsf.gov/nsb/committees/tr/index.htm>.

<sup>13</sup> National Science Board, Committee on Programs and Plans, Charge to the Taskforce on Transformative Research, December 16, 2004 (NSB/CPP/TR-04-1). Available online at: <http://www.nsf.gov/nsb/committees/cpptcharge.htm>.

<sup>14</sup> Members of the Task Force on Transformative Research were Kelvin K. Droegemeier, Regents' Professor and Weathernews Chair of Applied Meteorology, and Associate Vice President for Research at the University of Oklahoma-Norman; Nina V. Fedoroff (Chairman), Evan Hugh Professor, Willaman professor of Life Science, and Director of the Biotechnology Institute at The Pennsylvania State University, University Park; Kenneth M. Ford, Director of the Florida Institute for Human and Machine Cognition; Daniel E. Hastings, Director, Engineering Systems Division and Professor, Aeronautics and Astronautics and Engineering Systems at the Massachusetts Institute of Technology; Louis J. Lanzerotti, Distinguished Research Professor, Center

for Solar-Terrestrial Research, New Jersey Institute of Technology; Alan I. Leshner, Chief Executive Officer of the American Association for the Advancement of Science; Douglas D. Randall, Professor of Biochemistry and Director of the Interdisciplinary Program on Plant Biochemistry and Physiology at the University of Missouri-Columbia; and Kathryn D. Sullivan, President and Chief Executive Officer for the Center of Science and Industry. For more information: <http://www.nsf.gov/nsb/committees/tr/index.htm>.

<sup>15</sup> Workshop I, “Understanding Transformative Research Programs at the National Science Foundation,” was held on August 12, 2005, at the National Science Foundation in Arlington, Virginia. Workshop II, “Key Factors in Identifying and Fostering Transformative Science,” was held on December 16, 2005, at the Santa Fe Institute in Santa Fe, New Mexico. Workshop III, “Fostering Transformative Research: Views from Industry and Private Foundations,” was held on May 16, 2006, at the National Science Foundation in Arlington, Virginia. For more information: <http://www.nsf.gov/nsb/committees/tr/index.htm>.

<sup>16</sup> In its 2004 report, the AC/GPA noted, “the term ‘high risk’ with regard to research is still not clearly defined. It was not always clear to the Committee what characteristics NSF staff (program officers) making the designation ‘high risk’ were using to indicate which specific projects in the portfolio were deemed to be high risk... Projects may be classified as high risk not only because of the degree and/or nature of the innovation but also solely on the origin of the proposal (e.g., new researcher, context of the project” (2004, p. 14)). The Committee also found “considerable uncertainty” among Committee of Visitor (COV) reviews regarding the operational meaning of the term “high risk.” They suggested that this lack of an operational definition impedes the Foundation’s ability to properly assess how well they are funding such research and that the “definition of such research must be clear and widely understood by NSF’s key stakeholders” (2004, p. 14). They encouraged NSF to study the issue and recommended that NSF “separate the characterization of NSF-supported research into of that which is ‘innovative,’ that which is ‘high-risk,’ and that which is ‘multidisciplinary’” (2004, p. 15). The Committee also noted their preference for the term “bold” research over “high-risk” research (2004, p. 14). In response to the AC/GPA report, the Foundation asked its program staff in 2005 to identify projects they believed reflected “innovative-high risk” research and education. Based on 150 proposals that Program Officers identified as “innovative-high risk,” NSF came up with a rubric, which is included in the 2005 AC/GPA report. The AC/GPA applied the definitions outlined in the rubric to the 150 proposals and concluded, in their 2005 report, that NSF had made a “good start” in defining transformative research, but that “there is still work to be done in defining what constitutes transformative research” (2005, p. 16). This discourse, however, drops off in the 2006 AC/GPA report; the only mention of this discussion of definitions is a reference on page 53 to the 2005 AC/GPA report. Yet, the 2006 report itself highlights the continued ambiguity of the term. Throughout the report, “innovative,” “high-risk,” “high quality,” “transformative” are used synonymously. For example, on page 10 of the report, the AC/GPA reports identifying “227 projects as transformative” funded by NSF, but does not define what it means by transformative or how these were identified as such.

<sup>17</sup> Noonan, N. E., *Report of the Advisory Committee for the GPRA Performance Assessment: FY 2005* (Washington, DC: NSF, 2005) p. 16. Available online at: <http://www.nsf.gov/pubs/2005/nsf05210/nsf05210.pdf>.

<sup>18</sup> National Science Board, *Report of the National Science Board on the National Science Foundation’s Merit Review System* (Washington, DC: NSB-05-119, 2005), p. 1. Available online at: [http://www.nsf.gov/nsb/documents/2005/0930/merit\\_review.pdf](http://www.nsf.gov/nsb/documents/2005/0930/merit_review.pdf)

<sup>19</sup> *Ibid.*, p. 26.

<sup>20</sup> *Ibid.*, p. 8

<sup>21</sup> *Ibid.*, p. 3

<sup>22</sup> *Ibid.*, p. 10.

<sup>23</sup> Noonan, N. E., *Report of the Advisory Committee for the GPRA Performance Assessment: FY 2005* (Washington, DC: NSF, 2005), p. 36. Available online at: <http://www.nsf.gov/pubs/2005/nsf05210/nsf05210.pdf>.

<sup>24</sup> Rogers, G. M., *Report of the Advisory Committee for the GPRA Performance Assessment: FY 2006* (Washington, DC: NSF, 2006), p. 29. Available online at: <http://www.nsf.gov/pubs/2006/nsf06206/nsf06206.pdf>.

<sup>25</sup> Participants included Dr. Mark Fitzsimmons, Associate Director of the Fellows Program of the John D. and Catherine T. MacArthur Foundation; John Bruer, President of The James S. McDonnell Foundation; Dr. David Clayton, Director of the Howard Hughes Investigator Program, Howard Hughes Medical Institute; David Kingsbury, Chief Program Officer for Science of the Gordon and Betty Moore Foundation; Dr. Ray Kellman is Vice President of the Research Corporation; Dr. Elsa Reichmanis, Director of Materials Research at Bell Labs, Lucent Technologies; Dr. David Morse, Senior Vice President and Director of Corporate Research

at Corning, Incorporated; and Dr. Judith Greenberg, Principal Leader, Director's Pioneer Award Program, National Institutes of Health. For more information: <http://www.nsf.gov/nsb/committees/tr/index.htm>.

<sup>26</sup> Grant extensions are an NSF-wide mechanism specifically designed to support "innovative," "high-risk" or "creative" research. These mechanisms include "Accomplishment-Based Renewal Proposals" as well as a "Two-Year Extension for Special Creativity." Renewal proposals are requests for additional funding for a support period subsequent to that provided by a standard or continuing grant; renewal proposals compete with all other pending proposals. Creativity extensions allow researchers to explore high-risk research topics that emerge from, but are not covered by, an existing proposal. NSF's creativity extensions program is small. In FY 2000, there were 43 creativity extensions made to existing NSF grants. NSF's creativity extensions are initiated by the NSF Program Officer based on progress during the first 2 years of a 3-year grant.

<sup>27</sup> NSF high-priority research areas include (1) Nanotechnology, an inter-agency effort that supports the exploration of nanoscale phenomena and the development of new tools and techniques to facilitate a broad range of applications; (2) Biocomplexity in the Environment, a multidisciplinary effort that draws on new scientific and technological capabilities to investigate the interactions among ecological, social, and physical earth systems; (3) Human and Social Dynamics, which seeks to stimulate breakthroughs in knowledge about human action and development as well as organizational, cultural, and societal adaptation and change; and (4) Mathematical Sciences, which is designed to strengthen the mathematical foundations of science, technology, and society.

<sup>28</sup> Centers grants were established to encourage interdisciplinary and/or multidisciplinary collaborative research within universities, between universities and industry, and among other partners (such as National Laboratories and State/local governments). Centers Grants are designed to spawn new ideas and research methods while promoting innovative, potentially transformational results. Centers are selected through a multi-phase peer-review process.

<sup>29</sup> According to the program Web site, "The CBC Program is designed to support the formation of centers that can address major, long-term basic chemical research problems. Appropriate research problems are high-risk but potentially high-impact because they will attract broad scientific and public interest. Centers are expected to be agile structures that can respond rapidly to emerging opportunities and make full use of cyber infrastructure to enhance collaborations. Center teams may include researchers from other disciplines and from academia, industry, government laboratories, and international organizations." For more information: [http://www.nsf.gov/funding/pgm\\_summ.jsp?pims\\_id=9186](http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=9186).

<sup>30</sup> The Frontiers in Integrative Biological Research (FIBR) program encourages investigators to identify major understudied or unanswered questions in biology and to use innovative approaches to address them by integrating the scientific concepts and research tools from different disciplines. Other NSF organizational structures that may facilitate transformative research include the Office of Integrative Activities (OIA), which is responsible for overseeing and coordinating cross-Foundational activities, and the Office of Multidisciplinary Activities (OMA) in the Directorate for Mathematical and Physical Sciences (MPS), which is charged with facilitating and supporting opportunities that cross traditional disciplinary boundaries. In addition, the Research Coordination Networks program, also in BIO, creates networks of biological scientists working on common problems.

<sup>31</sup> More information about the National Science Foundation's Directorate for Engineering's Industrial Innovation and Partnerships Division (IIP). Available online at: <http://www.nsf.gov/eng/iip/about.jsp>.

<sup>32</sup> More information about the National Science Foundation's Directorate for Engineering's Civil, Mechanical, and Manufacturing Innovation Division (CMMI). Available online at: <http://www.nsf.gov/eng/cmmi/about.jsp>.

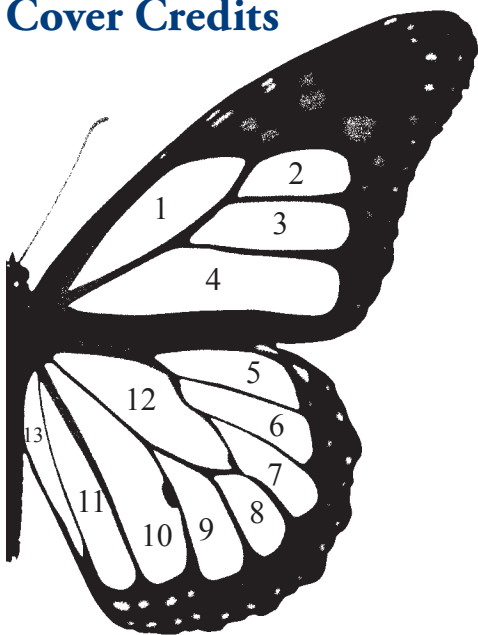
<sup>33</sup> Rogers, G. M., *Report of the Advisory Committee for GPRA Performance Assessment, FY 2006* (Washington, DC: NSF, 2006), p. 29. Available online at: <http://www.nsf.gov/pubs/2006/nsf06206/nsf06206.pdf>.

<sup>34</sup> National Science Board, *Report of the National Science Board on the National Science Foundation's Merit Review System* (Washington, DC: NSB-05-119, 2005), p. 10. Available online at: [http://www.nsf.gov/nsb/documents/2005/0930/merit\\_review.pdf](http://www.nsf.gov/nsb/documents/2005/0930/merit_review.pdf).

<sup>35</sup> *New NSF Director Speaks at AAAS Forum*, AAAS News Release, p. 1. Available online at: <http://www.aaas.org/news/releases/2005/0422bementText.shtml>.

<sup>36</sup> Rogers, G. M., *Report of the Advisory Committee for GPRA Performance Assessment, FY 2006* (Washington, DC: NSF, 2006), p. 14. Available online at: <http://www.nsf.gov/pubs/2006/nsf06206/nsf06206.pdf>.

## Cover Credits



### Image 1: Scalable Visualization using Grids

A visualization showing ground wave action as shock waves travel under the ocean, passing Catalina Island (in blue, upper left). This simulation, known as TeraShake, used the new 10 teraflops DataStar supercomputer and large-scale data resources of the San Diego Supercomputer Center (SDSC) at the University of California, San Diego.

Distributed interactive volume browsing with the Grid Visualization Utility, using the Globus Toolkit and a point-sampling technique to accelerate exploration of very large datasets. Showing the TeraShake-2.1 simulation depicting a velocity wavefield as it propagates through the 3-Dimensional velocity structure beneath Southern California. The warmer red and yellow colors indicate regions of compression, while the cooler blue and green colors show regions of dilation. Faint yellow (faults), red (roads) and blue (coast-line) lines add geographical context.

Credit: Marcus Thiebaut, Information Sciences Institute, University of Southern California

### Image 2: Ball Semiconductor

A spherical Semiconductor and MEMS Device Technology.

The unique technology foundation for which Ball Semiconductor Inc. (Allen, Texas) has been found. Although the technology has an obvious advantage of having a larger available surface area in a given foot print, the development of its materials, processes, device designs and fabrication methods have led to numerous new findings.

Credit: Research and photo by Component Technology Group at Ball Semiconductor Inc. (US Pat. 5,955,776; Akira Ishikawa (Founder) -- Spherical Shaped Semiconductor Integrated Circuit

### Image 3: Microhotplates

Microhotplates crafted of silicon carbide by Boston Microsystems, each consisting of a central plate surrounded by curved tethers. The largest is less than 100 microns (millionths of a meter) across.

These micro-hotplates--capable of reaching temperatures above 1100 degrees Celsius (2012 degrees Fahrenheit)--serve as a critical tool in developing new precision materials, some of which will enable the development of next-generation sensors. Already, the devices have led to new oxygen and engine emission sensors.

Credit: Boston Microsystems, Inc.; NSF

### Image 4: Tornado Simulation

This visual was created from data generated by a tornado simulation calculated on the National Center for Supercomputing Applications (NCSA) IBM p690 computing cluster. High-definition TV animations of the storm produced at NCSA were included in an episode of the PBS TV series NOVA called "Hunt for the Supertwister." The tornado is shown by spheres that are colored according to pressure: orange and blue tubes represent the rising and falling airflow around the tornado. (Date of Image: September 5, 2004)

Credit: Bob Wilhelmson, NCSA and the University of Illinois at Urbana-Champaign; Lou Wicker, National Oceanic and Atmospheric Administration's National Severe Storms Laboratory; Matt Gilmore and Lee Cronce, University of Illinois atmospheric science department. Visualization by Donna Cox, Robert Patterson, Stuart Levy, Matt Hall and Alex Betts, NCSA.

### Image 5: Sakhalin Island Project

A nymphalid butterfly *Inachis io*, from Southern Sakhalin Island, Russia.

The International Sakhalin Island Project is an international collaboration of American, Russian and Japanese scientists to survey the plants, lichens, mosses, liverworts, fungi, insects, spiders, freshwater and terrestrial mollusks, freshwater fishes, amphibians and reptiles of Sakhalin Island. Participating institutions include the University of Washington (Fish Collection, Burke Museum and Herbarium), the Russian Academy of Sciences, Far East Branch, and Hokkaido University, Hokkaido, Japan.

Credit: Photo by Trevor R. Anderson

### Image 6: Under the Antarctic Ice--Octopus

An octopus on bryozoan on the floor of McMurdo Sound. Deep under the Antarctic ice live teams of species of fish and other sea creatures like urchins, brittle stars and sea stars, jellyfish and sponges, worms and spiders, krill and shrimp, as well as marine mammals and penguins, to name a few. (Date of Image: January 11, 2005)

Credit: Henry Kaiser, NSF

### Image 7: Satellite image of gulf stream temperature

NSF sponsors a large and diverse research community that both uses and produces global change data and information. Although the NSF has no formal responsibilities for archiving and distributing data and information, it supports a major facility for meteorological, oceanographic, and climatology data sets at the National Center for Atmospheric Research (NCAR).

Credit: U.S. Global Change Research Information Office

### Image 8: LIGO

Laser Interferometer Gravitational-Wave Observatory (LIGO) scientists make adjustments to a mirror in the contaminant-free "clean room."

Credit: California Institute of Technology/NSF

### Image 9: Assembling the Tree of Life (ATOL)

A flood of new information, from whole-genome sequences to detailed structural information to inventories of earth's biota, is transforming 21st century biology. Along with comparative data on morphology, fossils, development, behavior, and interactions of all forms of life on earth, these new data streams make even more critical the need for an organizing framework for information retrieval, analysis, and prediction. Phylogeny, the genealogical map for all lineages of life on earth, provides an overall framework to facilitate information retrieval and biological prediction. Currently, single investigators or small teams of researchers are studying the evolutionary pathways of heredity usually concentrating on phylogenetic groups of modest size. Assembly of a framework phylogeny, or Tree of Life, for all 1.7 million described species requires a greatly magnified effort by large teams working across institutions and disciplines. NSF supports multidisciplinary teams to conduct creative and innovative research that will resolve phylogenetic relationships for large groups of organisms on the Tree of Life.

Credit: DNA, NSF Image Library

### Image 10: Biophotonics Research

Helium neon laser used for teaching and demonstrating biophotonics at the Technical Vocational Institute, an educational partner with the Center for Biophotonics Science and Technology (CBST). CBST is an NSF Science and Technology Center managed by the University of California, Davis.

Biophotonics is the science of generating and harnessing light (photons) to image, detect and manipulate biological materials. Biophotonics are used in many scientific disciplines, for example, in biology to probe for molecular mechanisms, function and structure; and in medicine to study tissue and blood at the macro (large scale) and micro (very small scale) organism levels in order to detect, diagnose and treat diseases in a way that is noninvasive to the body.

Credit: "Shedding Light on Life" -- NSF CBST, managed by the University of California, Davis.

### Image 11: Ocean Conveyor Belt

Newly published research results provide evidence that global climate change may have quickly disrupted ocean processes and lead to drastic shifts in environments around the world.

Although the events described unfolded millions of years ago and spanned thousands of years, the researchers, affiliated with the Scripps Institution of Oceanography, say they provide one of the few historical analogs for warming-induced changes in the large-scale sea circulation, and thus may help to illuminate the potential long-term impacts of today's climate warming.

Credit: Illustration by James J. Caras, NSF

### Image 12: Self-Assembly of Gold-Polymer Nanorods

This image depicts the self-assembly of gold-polymer nanorods into a curved structure. NSF-supported research by Chad Mirkin at Northwestern University has generated nanostructures with the ability to curve. These are the first nanostructures to exhibit this ability -- a critical requirement for the utility of nanomaterials in further applications including drug-delivery systems, nanoscale electronics, catalysts and light-harvesting materials. NSF is the lead agency for the National Nanotechnology Initiative, a multiagency network working to bolster nanotechnology and ensure U.S. dominance in this emerging field.

Credit: Chad Mirkin, Northwestern University

### Image 13: Periodic Table

How do massive stars explode and produce the heaviest elements in the periodic table? If we could design catalysts atom-by-atom, could we transform industrial synthesis? What strategies might be developed to optimize management of complex infrastructure systems? What kind of language processing can occur in large assemblages of neurons? Can we enable integrated planning and response to natural and man-made disasters that prevent or minimize the loss of life and property? Can we enable full reactive fluid flow, structural, dynamical and thermal simulation of combustion engines? Can we solve large-scale inverse problems leading to product, material, manufacturing process and supply chain synthesis and optimization? What are the thermal and mechanical properties of minerals at the temperatures and pressures encountered in the lower mantle and outer core of the Earth? These are just some of the important questions that researchers wish to answer using state-of-the-art High-Performance Computing (HPC) systems.

Credit: NSF Image Library

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Cover design by: James J. Caras, Design and Publishing Section, Information Dissemination Branch, National Science Foundation

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