ARISE 2

Unleashing America's Research & Innovation Enterprise

AMERICAN ACADEMY OF ARTS AND SCIENCES

American Academy of Arts and Sciences

Cherishing Knowledge, Shaping the Future

Since its founding in 1780, the American Academy has served the nation as a champion of scholarship, civil dialogue, and useful knowledge.

As one of the nation's oldest learned societies and independent policy research centers, the Academy convenes leaders from the academic, business, and government sectors to address critical challenges facing our global society.

Through studies, publications, and programs on the Humanities, Arts, and Education; Science, Engineering, and Technology; Global Security and Energy; and American Institutions and the Public Good, the Academy provides authoritative and nonpartisan policy advice to decision-makers in government, academia, and the private sector.

ARISE 2

Advancing Research In Science and Engineering

Unleashing America's Research & Innovation Enterprise

AMERICAN ACADEMY OF ARTS AND SCIENCES
Cambridge, Massachusetts

ISBN: 0-87724-095-7

The *ARISE II* report is available online at http://www.amacad.org/arise2.pdf.

The image on the outside cover was generated by using Wordle, a program created by Jonathan Feinberg, and it is based on the complete text of this report.

Please direct inquiries to:

American Academy of Arts & Sciences
136 Irving Street
Cambridge, MA 02138-1996
Phone: 617-576-5000

Email: aaas@amacad.org
www.amacad.org

American Academy of Arts and Sciences
ARISE II Committee

Venkatesh Narayanamurti (Harvard University), *Cochair*
Keith R. Yamamoto (University of California, San Francisco), *Cochair*
Nancy C. Andrews (Duke University School of Medicine)
Dennis Ausiello (Harvard Medical School)
Lawrence Bacow (Tufts University)
Malcolm R. Beasley (Stanford University)
Edward J. Benz, Jr. (Dana-Farber Cancer Institute)
David Botstein (Princeton University)
H. Kim Bottomly (Wellesley College)
Robert Brown (Boston University)
Claude Canizares (Massachusetts Institute of Technology)
Uma Chowdhry (DuPont)
Mary Sue Coleman (University of Michigan)
Alan Ezekowitz (Abide Therapeutics)
Harvey V. Fineberg (Institute of Medicine)
Mary L. Good (University of Arkansas)
Leah Jamieson (Purdue University)
Linda Katehi (University of California, Davis)
Neal Lane (Rice University)
Eugene H. Levy (Rice University)
Joseph B. Martin (Harvard Medical School)
Cherry A. Murray (Harvard School of Engineering and Applied Sciences)
Gilbert Omenn (University of Michigan)
Thomas D. Pollard (Yale University)
Robert C. Richardson † (Cornell University)
David D. Sabatini (New York University School of Medicine)
Randy Schekman (University of California, Berkeley)
Richard H. Scheller (Genentech, Inc.)
Henri A. Termeer (Genzyme Corporation, ret.)
Samuel Thier (Harvard Medical School)
Leslie C. Berlowitz, *ex officio* (American Academy of Arts and Sciences)

Project Staff
Kimberly Durniak (American Academy of Arts and Sciences)
Alison Fox (American Academy of Arts and Sciences)
John Randell (American Academy of Arts and Sciences)
Kelly Stewart (American Academy of Arts and Sciences)
Nathan Yozwiak (American Academy of Arts and Sciences)

Project Consultants
John C. Crowley (Charlottesville, Virginia)
Ann Reid (American Society for Microbiology)

† *Deceased*

American Academy of Arts and Sciences

Initiative on Science, Engineering, and Technology Oversight Committee

Contents

Preface

A*RISE II: Unleashing America's Research & Innovation Enterprise* tackles a broad set of issues facing the U.S. science and technology community. Although research in science and engineering is integral to America's health, security, and economic strength, there are persistent challenges to the vitality of this enterprise. Transdisciplinary and trans-sector research is essential to advance scientific discovery; government funding for scientific research is increasingly uncertain; and support for basic curiosity-driven programs, high-risk science, and young investigators is difficult to secure.

ARISE II has two overarching goals: 1) to promote a deep conceptual and functional integration across scientific disciplines; and 2) to foster cooperative, synergistic interactions among academia, government, and the private sector throughout the discovery and development process. If the nation wants to continue to attract both the domestic and international scientific talent required to address the challenges of our time, then we must reevaluate the organization of the U.S. research enterprise. Barriers to collaboration across sectors must also be addressed to ensure that fundamental advances are translated into new products and services.

Special appreciation to our dedicated cochairs, physicist Venkatesh Narayanamurti and biologist Keith Yamamoto. They worked with an expert committee drawn from across the physical and life sciences to craft a thoughtful and focused report. Members of the Academy's Oversight Committee on Science, Engineering, and Technology (page v) reviewed the final draft and provided many insightful and constructive comments. The committee also benefited from conversations with members of the President's Council of Advisors on Science and Technology and the National Academies' Committee on Research Universities.

ARISE II builds on the Academy's 2008 report *ARISE: Advancing Research In Science and Engineering: Investing in Early-Career Scientists and High-Risk, High-Reward Research*. Chaired by Tom Cech, Distinguished Professor at the University of Colorado Boulder and former President of the Howard Hughes Medical Institute, the first *ARISE* report addressed two critical issues: waning support for young investigators and the need to encourage potentially transformative research. The report continues to influence policy planning and philanthropic support.

We thank as well the many outside experts who participated in project workshops, including Maxmillian Angerholzer III (Richard Lounsbery Foundation), Robert Berdahl (Association of American Universities, ret.), Robert J. Birgeneau (University of California, Berkeley), Susan Desmond-Hellmann (University of California, San Francisco), Aled Edwards (University of Toronto), Steven Freilich (DuPont), Miles Klein (University of Illinois), David Korn (Harvard University), Tobin Smith (Association of American Universities), Larry Sumney (Semiconductor Research Corporation), Shirley M. Tilghman (Princeton University), Ellen Williams (BP; University of Maryland), and William Wulf (University of Virginia).

The Academy gratefully acknowledges support from the S.D. Bechtel, Jr. Foundation, the Richard Lounsbery Foundation, the Research Corporation for Science Advancement, the Michael and Susan Dell Foundation, the Gordon and Betty Moore Foundation, and the Hellman Foundation.

Despite the challenges facing the U.S. research enterprise, there are many promising avenues to strengthen it. New models of cooperation among academia, industry, and government can better enable scientists to meet the formidable challenges ahead. This report provides recommendations for accelerating the integration needed if America is to maintain its global scientific and technological leadership.

Leslie C. Berlowitz
President and William T. Golden Chair,
American Academy of Arts and Sciences

Executive Summary

Over the last fifty years, scientific and technological advances have transformed how long and how well we live, and they have been a vital ingredient in U.S. economic prosperity and security. These advances have brought us to a point of great opportunity, where unprecedented collaboration between disciplines can lead to the adoption of novel approaches to complex problems. Biologists, clinicians, physicists, computer and computational scientists, and engineers are finding broader and deeper collaboration to be increasingly rewarding. For example, interdisciplinary collaboration led to the determination of the human genome sequence just five decades after the structure of DNA was elucidated. In addition, there is enormous potential for such scientific advances to contribute to new technologies, commercialized by an innovative and internationally competitive private sector.

Efforts to take advantage of these opportunities, however, have met significant barriers. The current organization of the research sector complicates communication and collaboration across disciplines. Furthermore, fundamental advances are not being translated efficiently into new products and services. Both of these problems have historical roots. This report considers two broad sectors: the physical sciences and a primary venue for their application, engineering (PSE); and the life sciences and one of their major application areas, medicine (LSM). Throughout the last half of the twentieth century, advances in PSE were rapidly translated into a flood of innovative products. In turn, the quest for innovative technologies drove further advances in fundamental understanding. That is, in PSE, basic and applied research existed as an interwoven continuum. In contrast, the basic and applied life sciences were traditionally pursued as distinct and separate activities: life scientists focused on achieving a fundamental understanding of basic biological processes and until the dawning of biotechnology did not extend those discoveries into practical applications; for example, in medicine.

Despite these distinct historical set points, PSE and LSM now find themselves presented with a number of common challenges and opportunities. If these two sectors are to advance together, as they should, each must be mindful of the impact of their different histories on how challenges and opportunities are perceived and addressed. What are some of these common challenges and opportunities?

- *Dynamic and global economic challenges*: U.S. corporations face economic challenges that severely constrain their willingness to invest in fundamental science and technology research. Each generation of technology has a shorter competitive life span than the preceding one, and capital markets have little tolerance for long-term risk. Increasingly, if the most creative U.S. companies are to continue to derive new ideas from within the United States, the government must fund, and academia must generate, the discoveries that will drive the next round of innovative products. Yet establishing productive and sustainable collaborations between academia and industry has proven to be difficult. Parallel challenges exist in PSE and LSM education. Both sets of disciplines face increasing global competition to attract the best trainees and then to retain them to populate all sectors of the U.S. research enterprise.

- *Transdisciplinary opportunities*: The promise of interdisciplinary approaches has been noted for many years, and both universities and funding agencies have invested considerable effort into fostering such collaborations. However, both universities and funding agencies continue to be characterized by inflexible disciplinary and mission boundaries. Even the term *interdisciplinary*, which implies a space *between* disciplines, fails to convey the potential for integration across PSE and LSM. Perhaps *transdisciplinary* better captures the extent of integration required: it is the dismantling of disciplinary boundaries, rather than ad hoc collaborations, that could transform the scientific enterprise and deliver the potential to address previously intractable problems.
- *Urgent and formidable societal challenges*: The challenges facing society—from climate change to fossil fuel dependency to providing adequate food for a growing population—are immense, urgent, and intimately connected. With proper coordination, science and technology are poised to help solve problems at this level of complexity and importance. Larger-scale projects and collaborations need not—and should not—replace the more focused projects initiated and sustained by individual scientists. Indeed, *transdisciplinary* approaches to complex challenges will rely on the expertise and tools developed by many individual researchers. However, the collaborative pursuit of grand challenges can allow progress to accelerate beyond what individuals can accomplish alone.
- *Dated and inflexible policies and organizational structures*: Renovating dated organizational structures and cultural attitudes within and across the sectors could dramatically increase the availability of resources to enable transdisciplinary efforts. Some entrenched traditions, policies, and regulatory structures, while they made sense when implemented, have become counterproductive over time. Indeed, some policies now hamper progress.

Rapid progress is now within reach. A new model for cooperation and coordination among the stakeholders—the various disciplines within academia, many different government agencies, and a diverse set of for-profit and nonprofit private-sector entities—has been slow to emerge, possibly because no one part of the system can change in isolation. A coordinated effort will be required to reduce risks sufficiently for a critical mass in academia, government, and the private sector to try new approaches. This report from the American Academy of Arts and Sciences identifies two overarching goals and eleven recommendations that reach toward a new and powerful integration of PSE and LSM:

Goal 1:

Move from interdisciplinary to transdisciplinary

Moving toward transdisciplinary research will require more than encouraging researchers from different disciplines to work together. A critical next step is to provide incentives and remove barriers so that the tools and expertise developed within discrete disciplines are shared and combined to enable a deep conceptual and functional integration across the disciplines.

- ***Recommendation 1.1***
  Develop and foster a massive "knowledge network" that enables investigators from different disciplines to identify opportunities, establish collaborative efforts, and focus disparate expertise and approaches on problems of common interest.
- ***Recommendation 1.2***
  Expand education paradigms to model transdisciplinary approaches: Develop new and support existing graduate and postdoctoral training programs that integrate concepts and technologies across PSE and LSM.
- ***Recommendation 1.3***
  Expand support for shared core research facilities (especially those that span multiple PSE and LSM approaches), including funding for stable appointments of professional staff to direct them.
- ***Recommendation 1.4***
  Ensure that appointments and promotion policies recognize, support, and reward contributions to collaborative and transdisciplinary research and education endeavors.
- ***Recommendation 1.5***
  Better enable transdisciplinary research by scrutinizing current administrative policies, revising them to optimize efficiency and effectiveness, aligning incentives appropriately, and incorporating dynamic evaluation into future policies.

Goal 2:

Promote cooperative, synergistic interactions among the academic, government, and private sectors throughout the discovery and development process

Creating an interdependent ecosystem requires incentives for basic and applied research, development, and deployment. Novel discoveries can emerge during the development process, and new technologies can arise out of basic research labs. The academic, government, and private sectors must develop an inclusive and adaptive environment that ensures that the unique objectives, skills, and points of view of the different sectors are integrated and optimally utilized.

- *Recommendation 2.1*
  Establish one or more "grand challenges" that will motivate alignment, cooperation, and integration of efforts and approaches across academia, industry, and government. The magnitude and potential impact of these challenges should engage the scientific and engineering communities; inspire the next generation of science, technology, engineering, and mathematics students; and capture the public imagination.

- *Recommendation 2.2*
  Develop and implement new models for research alliances between academia and industry.

- *Recommendation 2.3*
  Enhance permeability between industry and academia at all career stages.

- *Recommendation 2.4*
  Set new priorities for the technology transfer function between academia and industry with the explicit goal of maximizing exchanges of knowledge, resources, and people.

- *Recommendation 2.5*
  Develop policies that focus on common interests between academia and industry, while acknowledging and managing intrinsic and avoidable conflicts.

- *Recommendation 2.6*
  Create mechanisms that increase coordination and cooperation among government agencies that support PSE and LSM.

Introduction

Scientific and technological innovations have been a cornerstone of U.S. economic vitality since World War II. However, there is growing concern that this engine of innovation is losing power and that the United States risks slipping from its position of global technological leadership. At the same time, society now faces problems in areas such as health, energy, the environment, and food security that are more urgent than ever. In response to these developments, the American Academy of Arts and Sciences convened experts to examine the state of the American research enterprise and to make recommendations to ensure its vitality, effectiveness, and sustainability.

The Academy released its first *ARISE* report in 2008. Chaired by Thomas Cech, then the President of the Howard Hughes Medical Institute, *ARISE I* focused on two issues central to the vitality of America's research enterprise: (1) the support of early career investigators; and (2) the encouragement of high-risk, high-reward research. The committee argued that such support and encouragement have the potential to foster a new generation of scientists and stimulate the daring investigations that will generate competitive advantage in a global economy.

Many of the *ARISE I* report's recommendations have been implemented. The NIH Director's Transformative Research Awards doubled to $70 million in 2010, and the fiscal year (FY) 2013 budget request for this initiative is $85 million. On January 14, 2010, U.S. Secretary of Energy, Academy Fellow, and ARISE I committee member Steven Chu announced that sixty-nine early career scientists would receive a total of $85 million in grants under a new Department of Energy (DOE) Early Career Research Program. The FY2010 budget recommendations from the White House Office of Science and Technology Policy (OSTP), headed by Academy Fellow John Holdren, also echo several key themes of *ARISE I*. For example, OSTP emphasized support for early career researchers, including a call to triple the number of National Science Foundation (NSF) graduate research fellowships by 2013. Holdren also asked that all executive departments and agencies prioritize high-risk, high-reward research in their FY2011 budget requests.

The Academy convened a second ARISE committee, chaired by Venkatesh Narayanamurti (Harvard University) and Keith Yamamoto (University of California, San Francisco), to explore additional aspects of the U.S. research enterprise where changes in policies and practices could have a positive impact. Taking a broad view, the ARISE II committee concluded that the most promising road forward will be found through comprehensive integration along two different, but complementary, axes.

First, the time is ripe for deep integration across disciplines, extending across the physical and life sciences and including both their basic discovery engines and their development and application efforts; in this report the latter are exemplified by engineering and medicine. What is both possible and necessary is a true conceptual leap from interdisciplinary collaboration to a powerful transdisciplinarity,[1] sweeping together the physical sciences and engineering (PSE) and the life sciences and medicine (LSM). Half a century ago, certain PSE industries hosted robust and outstanding basic and applied research and technology development, thus facilitating integration of efforts. In today's world, achieving integration even across just the PSE or LSM domain is challenging because basic and applied research are increasingly isolated from each other.

Occupying the second axis of integration are the stakeholders in the scientific research and innovation enterprise—academia, industry, and government. They must more effectively work together to plan and execute research and its applications and to implement policies, training programs, and mechanisms for funding and communications. Such an interdependent research ecosystem would hold great value for each stakeholder and would enable knowledge, tools, personnel, and funds to flow where they are needed. The committee was pleased to find extant pockets of success where some elements of the needed integration have been aggregated; these may serve as nucleation points for further integration. In other cases, policies that no longer serve their original purposes need to be replaced with new approaches that provide incentives for integration across disciplines and sectors.

To achieve these two overarching goals of a deep integration across PSE and LSM, as well as among academia, industry, and government, the committee advances eleven recommendations. Meeting these recommendations will invigorate the U.S. research and innovation enterprise, empowering it to maintain its global stature and to tackle critical societal challenges in health, energy, the environment, and agriculture.

1 By *transdisciplinary,* we mean to suggest an approach that represents a functional synthesis of methodologies and a broad point of view that combines different fields. This is a step beyond interdisciplinary, which borrows techniques from different fields without integrating them to yield new concepts and approaches.

Chapter 1: The Post-World War II Science and Engineering Research Enterprise

The contemporary research and innovation environment in the United States has its roots in the nation's massive research and development efforts during World War II. The war forged a new relationship among government, industry, and academia in the United States. The federal government addressed urgent wartime requirements for new weapons, transportation, and communication technologies by establishing many efforts targeted at specific needs, of which the best known was the Manhattan Project. Wartime pressure for rapid development of new technologies led to unprecedented cooperative arrangements involving academic, industry, and government scientists. Many of these successful projects were established and directed by Vannevar Bush, the director of the Office of Scientific Research and Development.

After the war, Bush was asked to develop a framework for postwar science and technology policy. Rather than propose a continuation of the government-managed collaborations that had proven so successful during the war, Bush's classic report, *Science—The Endless Frontier*,[2] urged broad federal support for basic academic research. Bush defined basic research as that which is "performed without thought of practical ends." This kind of research (also known as curiosity-driven, discovery research, or fundamental research) is sometimes criticized as being an aimless and inefficient approach to science, but Bush argued that it is in fact an extraordinarily powerful way to identify the most important unknowns and reveal entirely new opportunities. In his words:

> One of the peculiarities of basic science is the variety of paths that lead to productive advance. Many of the most important discoveries have come as a result of experiments undertaken with very different purposes in mind.

Bush emphasized that not all basic research will have practical impacts, but some unpredictable fraction will be groundbreaking:

> Statistically it is certain that important and highly useful discoveries will result from some fraction of the undertakings in basic science; but the results of any one particular investigation cannot be predicted with accuracy.

Finally, he pointed out that many new applications and technologies cannot even be imagined before the emergence of unexpected fundamental scientific discoveries:

> New products and new processes do not appear full-grown. They are founded on new principles and new conceptions, which in turn are painstakingly developed by research in the purest realms of science.

2 Vannevar Bush, *Science—The Endless Frontier: A Report to the President* (Washington, DC: United States Government Printing Office, 1945).

Bush argued that basic research, without a specific goal in mind, is vital to discovery and to the generation of new ideas that would find application in unexpected ways. Ultimately, Bush argued, the flow of ideas from basic research to application is a critical element in maintaining and extending American economic and technological leadership. The term *basic research* will be used throughout this report to represent the kind of fundamental, curiosity-driven, investigator-initiated research, with no practical goal in mind, that Bush believed to be so important to the overall innovative capacity of the research system.

Science—The Endless Frontier made a powerful argument for substantially increased government investment in basic research after the wartime emergency ended. However, government did not invest solely in basic research and was not the only stakeholder in the research sector. Government spending on applied research was substantial, especially for military purposes, but the private sector also invested heavily in research and development. All aspects of research must be considered interdependent and critical to innovation: basic research often contributes to practical advances, and applied research frequently leads to advances in fundamental understanding (see Sidebar 1).

Sidebar 1: The Complex Discovery and Innovation Ecosystem

"*A focus on the practical does not mean ditching fundamental science. It means using fundamental science for a purpose, and practical problems as a stimulus to curiosity…to [address] the big societal challenges of our times.*"[1]

Discoveries come from multiple pathways. For example, the "great thinkers" Albert Einstein and Niels Bohr contributed the theoretical underpinnings that led to unleashing the power of the atom. Conversely, Louis Pasteur, a practitioner, discovered fundamental biological principles in his quest to solve practical problems in the areas of sanitation and health.

These scientists shared the mindset that fundamental inquiries and basic research need not be separated from potential applications—even when the applications are not yet clear.

See Donald Stokes's *Pasteur's Quadrant*[2] for one view of the interplay between fundamental science, new technologies, and radical innovation.

1 G. M. Whitesides and J. Deutch, "Let's Get Practical," *Nature* 469 (2011): 21 – 22.

2 Donald Stokes, *Pasteur's Quadrant: Basic Science and Technological Innovation* (Washington, DC: Brookings Institution Press, 1997).

Much of the applied research investment, both public and private, flowed into the PSE disciplines, while research in the life sciences was overwhelmingly focused at the basic end of the spectrum. Accordingly, the postwar scientific culture in the PSE sector developed quite differently from that of the LSM sector, and these differences continue to distinguish and, in some respects, separate these fields.[3]

Historical Set Points in the Physical Sciences and Engineering

During World War II, substantial federal government investments in PSE reinforced a culture that placed basic and applied research on a continuum in which new discoveries were commonly motivated by, or resulted from, a challenge to accomplish a tangible goal. After the war, in response to the emerging tensions of the Cold War, several federal agencies (e.g., Department of Defense [DOD], the Atomic Energy Commission [precursor to the DOE], and the National Aeronautics and Space Administration [NASA]) continued to support mission-oriented research, providing funding for projects with specific national security goals. Government support for basic research in the PSE disciplines also substantially increased after the war with the creation of the NSF,[4] which was directed to support basic scientific and engineering research, as well as science and engineering education.[5]

In addition to the postwar increase in basic research funding from the federal government, the leadership of a few large companies (such as AT&T, DuPont, GE, IBM, and Xerox) had already recognized the benefits of conducting research at the scientific and technological frontier. Many of these companies became research powerhouses after having been involved in the successful wartime research and development efforts that yielded new scientific approaches and technologies in the quest to solve practical problems. To foster such an environment, these companies created centrally funded corporate research laboratories whose budgets were separate from business operations. The laboratories were insulated from any pressure to produce short-term, practical results but were never isolated from the corporation's compet-

3 The committee selected engineering as the major example of applied research using principles and approaches from the physical sciences; similarly, medicine was chosen to represent mission-oriented investigations using principles and approaches from the life sciences. The labels PSE and LSM are thus meant to be neither exclusive nor inclusive.

4 Established by the National Science Foundation Act of 1950, the NSF was authorized and directed to initiate and support basic scientific research and research fundamental to the engineering process; programs to strengthen scientific and engineering research potential; science and engineering education programs at all levels and in all the various fields of science and engineering; programs that provide a source of information for policy formulation; and other activities to promote these ends.

5 Other federal agencies also fund basic research in selected areas. For example, DOE continues to fund high-energy physics and basic energy sciences, and DOD supports research in condensed matter and materials physics.

itive challenges and market opportunities—thereby creating a climate that supported a free exchange of ideas. Organized as meritocracies, the industrial labs fostered a culture of excellence. Researchers were encouraged to explore high-risk ideas that were consistent with the goals of the corporation (see Sidebar 2).

The companies frequently had close relationships with academic scientists at universities and government scientists at the national laboratories. A relatively free flow of ideas, discoveries, technologies, and people across the public and private sectors was a familiar and valued part of the PSE culture, and the collaborations born during the war continued for several decades, serving as the growth engine of the American economy, as many innovations occurred outside the companies that originally funded the research.

Since the 1980s, dramatic economic and political transitions have influenced how PSE research is conducted and funded. For example, with the end of the Cold War, the strong mission orientation of the national laboratories became diffuse. A greater proportion of DOE funding, for example, went to basic research. More generally, basic research, applied research, and development increasingly took place in separate silos.

At the same time, the global economic environment became more competitive in the 1970s and 1980s, and many companies began to shift their resources toward short-term investments and returns, thereby diminishing their support for basic research efforts. At one time, significant corporate investment provided stable funding for a critical mass of in-house basic researchers. However, once certain large American corporations—particularly in the energy

Sidebar 2: The Delicate Balance of Freedom, Focus, and Funding

The Culture of the Great Industrial Laboratories

Meritocratic
- Recruited the best and the brightest
- Leadership was scientifically/technologically distinguished
- Fostered a culture of excellence through periodic performance reviews and mentoring

Stable Funding
- Allocation of a steady funding stream with long-term interests in mind
- Staffing focused in selected areas and with adequate funding to support each researcher

Balance between Freedom and Focus
- Research insulated but not isolated from goals of the corporation
- Vertical integration from research to development to application
- Technological advances in turn spurred new questions, enabled basic research, and generated new concepts and theories
- Collaboration across disciplinary boundaries to address the most challenging problems

and communications industries—lost their near-monopoly status,[6] investment in basic research began to disappear. Predictably, that decline in support resulted in a precipitous drop in scientific publications from those companies in primary PSE journals (Sidebar 3). Clearly, changes in economic conditions, maturing markets, increased competition, and ever-faster innovation cycles have affected how PSE research is conducted and funded.

Historical Set Points in the Life Sciences and Medicine

In LSM, the situation could hardly have been more different. Bush had argued for all scientific research to be funded by a single national research foundation and for that research to be funded strictly on the basis of scientific excellence, rather than according to practical concerns or government priorities. In the end, the NSF was much smaller in scope and funding than Bush had hoped. Its mission was to fund basic science and engineering research, but the lion's share of the government's life sciences funding bypassed the NSF and instead flowed into the National Institutes of Health (NIH), which had as its "use-inspired" mission the enhancement of human health.

Nevertheless, from the beginning, the NIH embraced the spirit of Bush's argument and instituted a peer-review system whereby scientists could identify meritorious basic research proposals without concern for potential practical applications. At the end of World War II, scientists had little to go on: the structure of DNA was unknown and the role of genes and their regulation in the origin and progression of disease was a black box. Life science researchers adopted Bush's philosophy and set out to understand fundamental biological processes, complying with the NIH requirement to include in their grant applications a sentence or two of speculation about how, for example, work on an obscure process used in bacteria to protect against invasion by foreign DNA might someday contribute to our understanding of human disease. (That very example led to DNA cloning, which in turn launched the biotechnology revolution.) Unlike the more integrated concepts in PSE, the notion that every fundamental life sciences discovery could advance the practice of medicine was virtually absent. Quite separately, physicians pursued their mandate to care for their patients using procedures established in their clinics.

This is not to say that discoveries made by basic biomedical researchers never contributed to the development of new drugs or treatments. However, until the mid-1970s, a life science industry did not exist, and any applications of basic discoveries in the life sciences were achieved by "crossover" efforts from PSE: pharmaceuticals emerging from applied chemis-

6 Companies once had considerable assured revenue sources, as many of them, especially in the electric power and communications sectors, were oligopolies with substantial barriers for others to enter the market.

Sidebar 3: Rise and Fall of the Industrial Labs

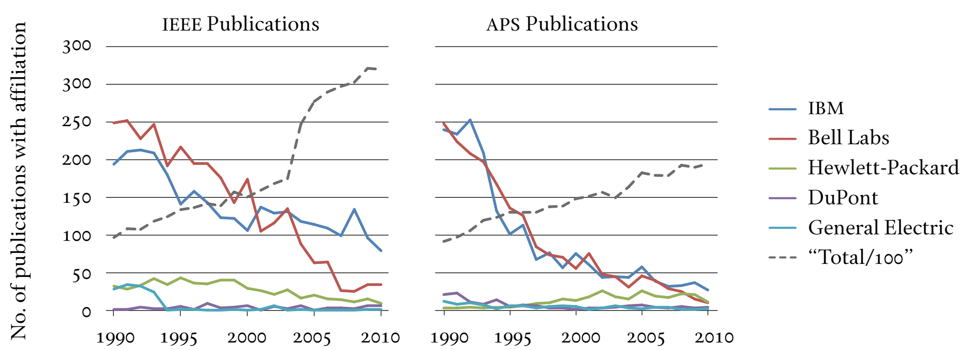
Established during the early part of the twentieth century, the corporate-funded research facilities concentrated teams of driven and visionary scientists and engineers. For example, companies such as IBM, AT&T, and GE maintained research programs comprising well-managed projects with a long-range focus that paved the way for their leadership in innovation. Transformative discoveries, contributing to the development of the integrated circuit, cellular telephones, and lasers, repeatedly materialized from these laboratories and were recognized by a number of Nobel prizes.

Some Nobel Prize-Winning Contributions from Industrial Laboratories

Activity	*Corporate Sponsor*	*Name of Researchers and Date of Prize*
Surface chemistry	GE Laboratories	Langmuir, 1932
Electron diffraction	Bell Laboratories	Davisson and Thomson, 1937
Transistor	Bell Laboratories	Bardeen, Brattain, and Shockley, 1956
Maser-laser	Bell Laboratories/Columbia Univ.	Townes, Basov, and Prokhorov, 1964
Quantum tunnel junctions	IBM T.J. Watson Laboratories/ GE Laboratories	Esaki and Giaever, 1973
Theory of disordered materials	Bell Laboratories	Anderson, Mott, and van Vleck, 1977
Cosmic microwave background radiation	Bell Laboratories	Penzias and Wilson, 1978
Scanning tunneling microscopy	IBM Zurich Research Laboratory	Binnig and Rohrer, 1986
High-temperature superconductivity	IBM Zurich Research Laboratory	Bednorz and Mueller, 1987
Quantum Hall effect	Bell Laboratories	Laughlin, Stormer, and Tsui, 1998
Integrated circuit	Texas Instruments	Kilby, 2000

Source : Reprinted from *Condensed-Matter and Materials Physics*, 2007, with permission from National Academy of Sciences, courtesy of National Academies Press, Washington, DC, based on data from http ://www.nobelprize.org.

The fundamental research results from these laboratories were often published in the open literature. Recently, however, these laboratories have shifted their focus away from long-term fundamental investigations and toward short-term, profit-driven research, and their representation in the public literature has dramatically declined.



Numbers of articles in American Physical Society (APS) and Institute of Electronic and Electrical Engineers (IEEE) publications that include authors from major industrial laboratories (1990 to 2010), compared to the total number of articles (divided by 100) published in the same journals.

Source data : IEEE Xplore Digital Library (http ://ieeexplore.ieee.org/).

try, medical devices from mechanical engineering, diagnostic imaging and radiation therapy from physics. The establishment of the biotechnology sector, led by Genentech in 1976, was a watershed. With a central goal to develop commercial applications of DNA cloning, by then a basic science tool that had itself arisen from fundamental biomedical research, a stream of other biotech companies appeared, founded by academic researchers and based on intellectual property generated in academia. In a few cases, prominent basic scientists were recruited to bring their research programs in-house and encouraged to pursue basic questions, on the assumption that their discoveries and their importation of an academic culture might contribute, eventually and not necessarily linearly or predictably, to the development of novel therapeutics. Several major pharmaceutical companies expanded their research departments to include basic molecular biology.

Despite the remarkable success of the biotechnology sector and the embrace of its approaches by the pharmaceutical industry, a functioning LSM continuum linking fundamental discovery and the care of patients remains, for the most part, a goal rather than a reality. While NIH promotes "translational research" and academic medical centers create programs to tap those resources, a concerned core of basic biomedical researchers points out that our understanding of biology remains both narrow and shallow and therefore that the untargeted research engine within LSM must remain strong. To many, this means that a clear separation must be maintained, with a vibrant and independent basic research sector protected from pressure to demonstrate applications for their findings.

This tension within LSM plays out in other ways. For decades, the standard of success in the biomedical research community has been the individual "investigator initiated" NIH award known within the community as an R01 grant, which supports a principal investigator and her or his laboratory space, equipment, students, and postdoctoral researchers to pursue a particular research project. Unlike PSE, where academic and industrial research have long been equally prestigious, involvement in and support from industry remains a stigma for some investigators, as well as for some academic promotion and tenure committees. Finally, the relatively generous scale of the NIH budget and its emphasis on funding individual LSM researchers has had numerous consequences in academia.

Conclusion

PSE and LSM have reached their current places by different routes, and consequently have distinct cultures and divergent experiences of interactions between basic and applied research, and among academia, industry, and government. The two sectors' different histories affect how each responds to calls for greater integration among disciplines, grand challenges, private-sector research, or academic-industry collaboration. By recognizing the differences in their cultures, and learning from each field's past challenges and successes, we have the opportunity to maximize the potential of the U.S. science and technology research enterprise. If government, industry, and academia can be incentivized to work together in new ways, the different approaches to creativity and innovation developed over the years in these very different sectors can be integrated and expanded to their mutual benefit.

Chapter 2: Adjusting to a New Playing Field

Despite their different historical traditions, PSE and LSM now find themselves contending with several common forces. The public and private sectors and academia are all struggling to adapt to new worldwide economic realities and to societal challenges that are global, interconnected, and urgent. Fortunately, scientific advances are creating tremendous opportunities for disciplines to work together in new ways. However, traditional policies and organizational structures are making it difficult for new approaches to be explored and new opportunities pursued. PSE and LSM have, as it were, a new opportunity to play on the same team, but field conditions are rapidly changing, and the strategies and rules of the new game have not yet emerged.

Dynamic and Global Economic Forces

U.S. corporations face economic challenges that severely constrain their willingness to invest in fundamental science and technology research. Emerging economies in China, South Korea, and India are joining, and threatening to surpass, traditional U.S. competitors in Europe and Japan. These nations are vigorously supporting science and technology research, and their corporations are increasingly technologically sophisticated. U.S. corporations must be able to compete in the global market, where the competition is driven not only by economic forces but also by capacity for innovation. Each technological advance seems to have a shorter competitive life span, and capital markets have little tolerance for long-term risk. Corporations have abandoned long-term, open-ended research agendas in favor of timelines centered on short-term profits. Even large pharmaceutical companies with strong cash balances are closing facilities and pulling back from "in-house" discovery research. U.S. companies are pushing some research and development activities overseas, raising concerns that competitiveness will suffer if the United States fails to maintain a home base sufficient to sustain a high-tech work force. In PSE, this trend began in the 1970s and accelerated in the early 1990s when the "engines of innovation" of the past (e.g., Bell Labs, Xerox PARC, General Electric, IBM, and DuPont) further reduced their basic research portfolios. Thus, for both LSM and PSE, government must support and academia must generate the discoveries that will fuel innovative applications in the private sector. This formula underscores the need to derive collaborative approaches between academia and industry that are more effective and productive than most now in place.

The public sector also faces economic constraints. The United States is just emerging from a prolonged economic downturn and sustained high level of unemployment, and continued concerns about government debt and unsustainable healthcare costs have created heavy pressure on government spending. In an era of lower tax revenues and many competing demands on spending, a compelling case can nonetheless be made that research spending has been a key driver of U.S. economic vitality and that stagnation or reduction of government support for research would be a shortsighted policy choice.[7] Furthermore, new scientific and technical capabilities, combined with flexible and collaborative organizational approaches, are expanding the opportunities for research funding to have a positive economic impact.

Formidable, Urgent, and Interconnected Societal Challenges

The need for continued research investment is underlined by the urgency of societal problems that are increasingly global in nature and cannot be solved by any one discipline or sector.[8] Challenges such as attaining energy independence while reducing carbon emissions, achieving "precision medicine," developing sustainable food production, and preserving the ecosystem services on which human life depends will all require advances across PSE and LSM and will require government, academia, and industry to work together. For example, precision medicine—in which medical treatment is tailored to the particular genetics, personal history, and behavior of individual patients—means that a vast amount of data must be collected and complex, interacting disease mechanisms understood at a level that allows specific intervention at the right time for each individual.[9] Handling this level of complexity will require approaches from physical sciences, engineering, information sciences, environmental sciences, and social sciences, together with an ever-more sophisticated understanding of the underlying biology.

The goals of precision medicine and sustainable food, energy, and ecosystem services present opportunities to develop "grand challenges" that could capture the imaginations of scientists, engineers, students, and the public at large (see Sidebar 4). With proper coordination, science and technology are poised to solve problems at this level of complexity and importance. Larger-scale projects and collaborations cannot—and must not—replace the more focused projects initiated and sustained by individual scientists. Indeed, complex challenges will rely on the expertise and tools developed by many individual researchers. However, a ringing enunciation of a grand challenge could inspire broadly collaborative investigations and the development of new technologies that are essential for achieving the challenge—both rates and extents of progress far beyond what individuals could accomplish alone. Creating opportunities for many researchers to continue their individually funded projects *and* contribute their specialized knowledge to larger efforts will leverage the advances made in individual laboratories.

7 National Research Council, *Rising above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future* (Washington, DC: National Academies Press, 2007).

8 *A New Biology for the 21st Century* (Washington, DC: National Academies Press, 2009).

9 National Research Council, *Toward Precision Medicine: Building a Knowledge Network for Biomedical Research and a New Taxonomy of Disease* (Washington, DC: National Academies Press, 2011).

Sidebar 4: Grand Challenges

Beginning during World War II and continuing through the Cold War, PSE was called upon to rise to grand challenges—responding to dramatic national needs with inspiring new research. Efforts such as the Manhattan Project and the Apollo missions were not only successful in meeting explicit goals; they also inspired generations of students, reinforced the public's belief in and support for science and engineering, and spawned innumerable, unanticipated discoveries and technologies. The moon launch, like the targeted missions of World War II, had a specific and clearly delineated goal that could be achieved only by a large-scale collaborative effort. The necessary scientific and technological capacity was not in place when the goal was set, but the needs were clear and the appropriate advances were made in service to the overall mission.

By contrast, many of the large-scale collaborative efforts conducted in the life science and medicine took on dynamic challenges and had unknown end points. For example, the War on Cancer, launched by President Richard Nixon in 1971, provided funding for basic research aimed at understanding the basic biological mechanisms underlying cancer. Tremendous advances were made that expanded our understanding of the complexity, heterogeneity, diagnosis, and treatment of cancer. Indeed, many discoveries were made with implications well beyond cancer, but no "man on the moon" moment demonstrated that the War on Cancer had been won. Responding to the AIDS pandemic was not explicitly named as a grand challenge, but the substantial and international commitment to funding research on HIV and AIDS has yielded tremendous advances in immunology, molecular virology, and epidemiology. Success in tackling such a multifaceted health crisis highlights the increasingly global nature of health challenges and demonstrates the value of facilitating international collaboration. The first genuine grand challenge in the life sciences, the Human Genome Project (HGP), had an explicit end point that was achieved ahead of schedule and under budget. Importantly, the HGP also stimulated the development of high-throughput, inexpensive sequencing technologies that have transformed life sciences research and are starting to transform medicine.

What these efforts have in common is the development of a multipronged, multistakeholder approach to address a challenge. Each project exemplifies the innovative problem-solving skills of researchers from a variety of fields and demonstrates the value of private and public partnerships. Each meets the most important criterion for the kind of goals that a grand challenge should address; that is, "to produce a public good—an end product that is valuable for society and is useful to many or all investigators in the field."[1]

The following insightful list of criteria for the selection of grand challenges comes from a 2001 National Research Council report, *Grand Challenges in the Environmental Sciences*:[2]

- Compelling—offering the potential for a large payoff in both scientific and practical terms
- Large—requiring numerous researchers, many years, and appropriate resources
- Relevant—addressing issues of importance to humankind
- Feasible—likely to result in significant progress within a decadal time span
- Timely—areas in which recent technological or scientific advances will have a particularly high impact
- Multidisciplinary—the challenge should serve to build capacity for multidisciplinary research that would have spillover benefits to multiple disciplines.

---

1 National Cancer Policy Board, *Large-Scale Biomedical Science* (Washington, DC: National Academies Press, 2003), 19.

2 National Research Council, *Grand Challenges in the Environmental Sciences* (Washington, DC: National Academy Press, 2001). Also see National Academy of Engineering, *Grand Challenges in Engineering* (Washington, DC: National Academy of Engineering, 2008), www.engineeringchallenges.org; and Gilbert S. Omenn, "Grand Challenges in Science, Technology, and Society," *Science* 314 (2006): 1696–1704.

Transdisciplinary Opportunities

Despite economic pressures and substantial societal challenges, the committee sees reasons for optimism. Investments in research over the past sixty years are richly paying off. Research fields are evolving, and the lines among disciplines are blurring, leading to the emergence of new fields of study that span disciplinary boundaries and allow dramatic advances that no one field could have achieved in isolation. Even traditional disciplines as they are defined today differ substantially from their initial incarnations. LSM increasingly relies on sophisticated instrumentation, intensive computational resources, and systems approaches that depend on close collaboration with PSE. PSE-derived nanotechnologies are bringing applications of quantum mechanics to the real world and advancing breakthrough technologies such as quantum cryptography and computation. Supercomputing is making simulation a critical component of both PSE and LSM, making modeling an increasingly powerful tool to complement theory and experimentation. Perhaps most important, PSE and LSM are moving toward a common language: advances in mathematics, information sciences, and computer engineering allow highly diverse kinds of data to be manipulated in digital form, and this capability will help unlock problems across scientific disciplines.

The committee concludes that the objective is to achieve transdisciplinarity—to integrate fields beyond the levels of the *multidisciplinary*, in which multiple disciplines operate simultaneously, or the *interdisciplinary*, which occupies the space between disciplines. In the term *transdisciplinary*, the committee sees leveraging of existing concepts and approaches from multiple disciplines to derive new concepts and approaches, which in turn enable new ways to achieve and utilize understanding. Hence, *transdisciplinary* implies an integration-driven emergence of new disciplines, not just ad hoc collaborations. For example, a transdisciplinary, systems-level approach to the workings of a cell might merge expertise in molecular and evolutionary biology, chemistry of small molecules and macromolecules, physics of energy storage and transfer, network and chaos theories, mechanical and systems engineering, and much more, each contributing a layer of information that can integrate to a new level of understanding. Similarly, developing economically and ecologically viable replacements for fossil fuels might engage expertise in chemical, systems, and environmental engineering, microbiology, plant science, ecology, computational science, economics, the science of social change, and more. The *transdisciplinary* nature of current scientific and societal challenges—and the powerful new approaches enabled by the combination of traditionally separate disciplines—can be fully addressed only by a rethinking of current academic and government funding structures, as well as the traditional relationships among academia, the private sector, and government.

The individual disciplines, each supported by specialized funding programs in separate agencies, have been extremely effective at increasing the body of knowledge over the last fifty years. Furthermore, the development of deep expertise in a particular area must continue to be a critical goal of graduate and postdoctoral education—the idea is not for "everyone to know everything." But traditional academic departments are often isolated from one another, separated into distinct schools of medicine, engineering, agriculture, and basic sciences. Results are published in specialized journals and presented at specialized meetings. The sheer volume of published research makes staying current even in a specialized field, much less across all of science, virtually impossible. And federal funding is distributed across dozens of specialized agencies, each with its own mission and culture, each motivated to look distinct and separate from the other agencies in the eyes of congressional appropriators. These conditions make collaboration, or even interaction, difficult across disciplines or the boundaries of agency missions. Furthermore, despite the increasingly global nature of science, international collaborations are clumsily supported at best.

A radical expansion of transdisciplinary research will require many changes. Academia will have to evolve new ways to define success. Information accessibility will require significant attention and investment. Agencies will need encouragement and permission to be more flexible in their approaches to fulfilling their missions. The private sector will need a new kind of thinking about intellectual property and investment in basic research. All of the sectors will need to increase cooperation, ideally bringing together the best researchers and companies for any given task, both within and outside the United States.

Evaluating and Updating Administrative and Regulatory Policies

The scope and practice of research across the PSE and LSM spectrum has been undergoing dramatic change for over a quarter century, yet few of the policies that fund and govern it have been reviewed and evaluated. Within the framework of advancing transdisciplinary research, examination and modification of certain federal administrative and regulatory policies could increase efficiency and decrease costs for both investigators and administrators. In view of current economic pressures, cost savings resulting from such policy revisions could help to support novel transdisciplinary initiatives.

To illustrate the breadth of these issues and the potential impact of addressing them, the committee considers several examples:

1. In the LSM sector, NIH permits payment of up to almost full investigator salaries from direct costs and up to full payment of capital construction from indirect costs. These policies create an incentive for universities and research institutes to build new facilities to house newly recruited investigators, especially during times of federal funding booms. With the inevitable arrival of bust years, competition for shrinking resources intensifies to a breaking point, productive investigators lose support, grant applications and reviews become more conservative and incremental, and bright

trainees choose other careers or pursue opportunities abroad. Moreover, these policies consume a substantial portion of the NIH budget, funds that could be allocated to support transdisciplinary research itself, rather than for salaries and building expenses. What is needed is a thoughtful dialogue between research institutions and the federal government about shifting to the institutions a greater responsibility for covering these costs. While these changes will be painful and must be installed gradually in order to protect institutional viability, the current situation is unsustainable.

2. In the PSE sector, support for graduate education is mission-critical for the NSF but not for DOE, a major funder of PSE research. As a result, DOE lacks a formal training program, and DOE grants do not provide significant funding for graduate students, a serious impediment to creating a transdisciplinary research culture.

3. Research across LSM and PSE is supported by dozens of federal agencies, each with a separate mission, each competing with the others for its share of the federal budget. The fragmentation of government science funding can be an impediment to flexible, transdisciplinary projects. To choose just one example, shared multidisciplinary facilities providing advanced sequencing, imaging, and computational resources would be equally useful to research in human health, biofuels, and crop plant breeding. However, no process exists by which the NIH, U.S. Department of Agriculture, and DOE could jointly[10] plan and fund such laboratories for the benefit of all. Consequently, cooperative arrangements and shared facilities are uncommon, and funding of joint projects and facilities is cumbersome and rare; notably, the budgets of different agencies are typically determined by different congressional committees.

Efforts to develop interagency research projects are further hampered by agency-to-agency differences in peer review, investigator or program origination and management of projects, and approaches to public-private partnerships. Consideration should be given to development of small experimental programs in which two agencies agree to jointly oversee a program using a policy or practice of one agency that diverges substantially from that of the other. For example, DOD's Defense Advanced Research Projects Agency (DARPA) gives its program managers considerable autonomy in funding decisions and project oversight for research programs that commonly include investigators from industry and academia. This applied goal-focused approach is being emulated experimentally in DOE's ARPA-E program, and DARPA itself has been funding some LSM-focused projects. The committee would like to

10 That is, offer one grant supported by various agencies, rather than each agency providing an individual grant for the same facility.

see an agency with quite different practices devise a joint experimental program together with DARPA to seek jointly a high-impact breakthrough using DARPA-like approaches.

4. Federal requirements concerning conflict of interest, regulatory oversight and compliance, grant administration and tracking, and other administrative reports have expanded ad hoc with the emergence of each new issue and without apparent regard to their coordination or their overall burden. Lacking ongoing assessment, such requirements can become entrenched even if ineffective, counterproductive, or beyond their useful lifetime. Cost and time implications for both federal agencies and universities are substantial. A concerted effort to streamline reporting requirements and make them consistent across agencies would liberate resources to support research.

Inefficient Policy Environment

We face many global challenges in the twenty-first century: predicting the impact of climate change and providing tools for adaptation and mitigation, developing sustainable sources of energy, providing enough food with limited arable land and water resources for an increasing population, and meeting the growing healthcare needs of aging populations. Scientific and technological advances have the potential to contribute to addressing each of these challenges. Yet a new model for cooperation and coordination among the players—academia, government, and industry—has been slow to emerge, possibly because no one part of the system can change in isolation. A coordinated effort will be required to sufficiently lower the risks for a critical mass in academia, government, and the private sector to try new approaches. The recommendations presented in this report illustrate the breadth of changes needed to construct a more creative and flexible research ecosystem.

Chapter 3: Recommendations

In the twenty-first century, the full promise of the research enterprise can be realized only if problems are approached in a transdisciplinary manner and if discovery and application are seen as complementary aspects of a continuous, iterative process. Basic researchers and the scientists, clinicians, and engineers who apply their discoveries must be aware of one another's capabilities and be able to form and dissolve working partnerships as needed. Sometimes this cooperation will manifest itself as a vertically integrated team that works together throughout the development process. Other times, discovery and innovation will emerge through more fluid collaborations or simply as individual researchers become more aware and capable of integrating advances made in other disciplines. Whether progress is to be achieved by dedicated teams or through more-rapid assimilation of advances by individual researchers, the organizational, informational, and cultural barriers that currently isolate disciplines and impede cooperation across sectors must be lowered. The committee therefore promotes two broad goals for the U.S. science and technology sectors: an accelerated integration across disciplines and the creation of an environment that allows flexible interactions among the academic, government, and private sectors throughout the discovery and development process.

To realize those goals, the committee offers eleven specific recommendations, each directed to one or more stakeholder groups. In aggregate, the recommendations illustrate the range and scope of changes that are necessary in order to increase incentives for collaboration and lower the risk of new approaches.

Goal 1:

Move from interdisciplinary to transdisciplinary

Moving toward transdisciplinary research will require more than encouraging researchers from different disciplines to work together. A critical next step is to provide incentives and remove barriers so that the tools and expertise developed within discrete disciplines are shared and combined to enable a deep conceptual and functional integration across the disciplines.

Across the United States and around the world, some researchers are already working across disciplinary boundaries, and some institutions are developing programs and centers to take advantage of the new opportunities. However, the potential for innovation is even greater than current approaches allow. The committee offers five recommendations to facilitate the transition from interdisciplinary to transdisciplinary approaches.

- **Recommendation 1.1** *(to academia and government)*

  Develop and foster a massive "knowledge network" that enables investigators from different disciplines to identify opportunities, establish collaborative efforts, and focus disparate expertise and approaches on problems of common interest.

Tools like Google Scholar and PubMed already make scientific literature more accessible than ever before. But scientific papers are written in the jargon of their disciplines and published in highly specialized journals. An online, visualized network that can reveal unexpected links between investigations in different fields or disciplines or suggest the deployment of new technology from one field into a different field could create a new research agenda and suggest new collaborative approaches. The development of a "Library of Congress" for the whole of scientific knowledge could be an immensely powerful means of leveraging scientific information, much of which is not readily comprehensible to the people whose research might thereby be transformed. The Obama administration's recently announced policy on open access to scientific literature is a step in the right direction.[11]

A 2010 presidential task force report requested by the Office of Science and Technology Policy notes the need to tackle the problem of massive scientific datasets. The report concludes that the nation is underinvesting in its data infrastructure, a conclusion that provided the justification for a $200 million "Big Data Research and Development Initiative" announced in March 2012.[12] This initiative is most welcome and is consistent with the committee's conclusion that a great deal is to be gained by ensuring that the information generated by our scientific enterprise is put to the fullest possible use.

A recent National Research Council (NRC) report promotes the concept of a knowledge network and information commons for human health information.[13] Expansion of this idea to the development of a common platform for the physical sciences and engineering as well as life sciences will require a substantial investment of resources and imagination. At present, we can conceive only a vague outline of such an infrastructure. If achieved, this endeavor would

11 John Holdren, "Increasing Access to the Results of Federally Funded Scientific Research," Memorandum for the Heads of Executive Departments and Agencies, Executive Office of the President, Office of Science and Technology Policy, Washington, DC, February 22, 2013.

12 Tom Kalil, "Big Data Is a Big Deal," *Office of Science and Technology Blog,* March 29, 2012, http://www.whitehouse.gov/blog/2012/03/29/big-data-big-deal.

13 National Research Council, *Toward Precision Medicine*.

result in the creation of a virtual research community accessible across academia, government, and industry. This knowledge community would not be limited by physical proximity to universities or to corporations large enough to have their own basic research capabilities.

Such a resource would make it far easier for federal funding agencies to leverage their investments in research, avoid competition or needless duplication, and identify promising developments outside their immediate portfolios. It would allow individuals from academia, the private sector, and federal agencies to find the collaborators necessary to move their projects forward. And it could provide readily searchable and sortable access to vast stores of information, including new concepts and new methods, transdisciplinary funding opportunities, funded projects, patent filings, clinical trial results, public-private research ventures, transdisciplinary research centers, core facilities, and transdisciplinary training programs.

Developing such a knowledge network would in and of itself be a transdisciplinary endeavor. A series of workshops should be held to develop a vision and plan for the knowledge network, bringing together experts from many stakeholder groups, including experts from diverse academic disciplines, the private sector (e.g., social network and search engine developers), and funding agencies.

- ### Recommendation 1.2 *(to academia and government)*

  Expand education paradigms to model transdisciplinary approaches: Develop new and support existing graduate and postdoctoral training programs that integrate concepts and technologies across PSE and LSM.

Traditionally, graduate students in Ph.D. programs, medical research fellows, and postdoctoral trainees develop a strong sense of departmental identity, both because departments cover costs for their training and because departments offer a discipline-based academic home. As disciplinary lines blur and scientific careers increasingly benefit from transdisciplinary collaborations, research trainees would benefit from changes that provide more mobility across departmental and even school boundaries. Some universities have begun to develop such programs with support from several funding agencies (see Appendix II), but many more such programs are needed. A comprehensive compendium of all such programs would provide a directory of innovative programs, identify best practices, and highlight potential gaps and opportunities for collaboration.

Another approach that has proven successful both for training and for midcareer exposure to new disciplines is that of intensive transdisciplinary summer courses. Some of these courses, such as those offered at the Woods Hole Marine Biological Laboratory and Cold Spring Harbor Laboratory, have been offered for over a century. A recent report by the American Academy of

Microbiology evaluates the impact of such courses and concludes that, while labor-intensive, they are uniquely effective at introducing students to transdisciplinary approaches and fostering long-term collaborative relationships.[14]

Graduate education should be an explicit part of the mission of all federal agencies that support research. For example, creating and funding graduate training grants across the research scope of DOE would enable transdisciplinary training that is vital to solving grand challenge problems. Cross-agency coordination of policies, requirements, and formats for such training grants should be a priority.

- ### Recommendation 1.3 *(to academia, government, and industry)*

  Expand support for shared core research facilities (especially those that span multiple PSE and LSM approaches), including funding for stable appointments of professional staff to direct them.

Research relies on costly resources (e.g., extensive facilities to house and care for model animals, large telescopes for astronomy research) and rapidly advancing technologies that require specialized expertise to generate and interpret high-quality data (e.g., high-throughput screening, advanced imaging capabilities, high-performance computing). Increasingly, researchers rely on shared facilities that divide costs, provide stable leadership, and include staff who contribute technical expertise to multiple research projects. The shared facilities contribute to progress on several fronts: they provide career options for talented trainees who are drawn to team-oriented, multidisciplinary research; they can act as a hub between researchers from different departments and disciplines; and they can serve as neutral spaces where collaborations can be fostered between academic and private-sector researchers. These facilities can also ensure the availability of expert support and cutting-edge instrumentation to individual research teams.

Successful models for shared research facilities include small, shared core facilities at individual institutions and large-scale, independent centers. Facilities may serve academic researchers (e.g., NSF synthesis centers), or provide opportunities for government-academia interaction (e.g., the national laboratories), or foster public-private interaction (e.g., industrial facilities that are open for use by academic researchers in exchange for intellectual property rights). Funding models for such centers are also varied and include fee-for-service, staff-procured grants, or short-term, start-up funding with the goal of eventual sustainability through grant

14 Ann Reid, *Educating the Microbiologist of the Future: The Role of Summer Courses* (Washington, DC: American Academy of Microbiology, 2011), http://academy.asm.org/images/stories/documents/Summer_Courses.pdf.

funding. As a resource for agencies, universities, and private companies interested in developing such facilities, the committee recommends a comprehensive evaluation of alternative models of shared facilities, as well as case studies aimed at identifying best practices. These facilities should serve both convening and enabling functions and might in principle be funded jointly by two or more agencies.

• Recommendation 1.4 *(to academia)*

Ensure that appointment and promotion policies recognize, support, and reward contributions to collaborative and transdisciplinary research and education endeavors.

Although transdisciplinary, team-based science has tremendous potential to solve new kinds of problems and provide a more seamless interaction between discovery and development, the most secure academic career path still passes through university departments where criteria for appointments and promotions emphasize discipline-based, individual achievement measured by individual funding and scholarly publications. Traditional criteria in some scientific departments, especially within LSM, discount collaborative work when a faculty member is not the senior author or when results are published in specialized journals outside the department's core discipline. They assign little value to other activities that accelerate the translation of research for public benefit. Evaluation of candidates for appointments, promotions, and tenure relies heavily on reference letters written by external experts who compare the candidate to others in the same field. Each of these approaches disadvantages individuals who are essential members of transdisciplinary teams and individuals whose work bridges disciplines or falls in the interstices between disciplines.

Although universities are beginning to recognize the importance of collaboration across disciplines, the interests of individual departments (as reflected in their budgets, space, and course allocations) still frequently come into conflict with creating the best possible environment for genuinely transdisciplinary scholarship. To lower the barriers that are inherent in the traditional academic organizational structure, universities must be encouraged not only to reward departments for recruiting and retaining transdisciplinary scholars, but to develop stable career tracks that cross or exist outside departments. The committee offers the following suggestions:

1.4.1 Develop guidelines to recognize the specific contributions of collaborators to cooperative research efforts, such as multi-investigator grants and publications, and to dynamic research teams assembled to approach particular problems. One approach is to attribute explicitly the contribution(s) of each author as is done in certain fields with long traditions of managing authorship issues for team-based projects. These examples should be studied for possible usefulness in transdisciplinary work.[15]

1.4.2 Give greater weight to the public service criterion in promotion evaluations and consider knowledge export activities, including entrepreneurship, to be a component of public service.

1.4.3 Set aside a fraction of faculty appointments for scientists and engineers who bridge traditional departments or schools, facilitate migration across these boundaries as fields or interests change, and allow departments to compete for these slots. In addition, develop appropriate advancement models to reward and retain transdisciplinary researchers.

• Recommendation 1.5 (*to academia and government*)

Better enable transdisciplinary research by scrutinizing current administrative policies, revising them to optimize efficiency and effectiveness, aligning incentives appropriately, and incorporating dynamic evaluation into future policies.

The academic research enterprise faces considerable financial uncertainty; its current position may be economically unsustainable. Many researchers are dependent on "soft" money to support their salaries, yet success rates in applying for research project grants, which include salaries, research costs, and indirect costs, are at all-time lows. Such scenarios have implications well beyond this report's focus on the need to encourage transdisciplinary and team-based science, and they underscore the fact that federal support for the research enterprise typically touches all elements of the endeavor. Carving a shrinking dollar into many pieces does little to encourage enthusiasm for research careers, especially in areas that are unconventional and risky.

15 Authorship guidelines are well documented in some fields. For example, in high energy physics authors must have made a major contribution to the construction or operation of the detector or have responsibility for a large inventory of service tasks such as calibration, important software contributions, and performance studies. These guidelines take into account varying time commitments among such categories as student, postdoc, and faculty member and typically include a "sunset" clause to handle personnel departures from a collaboration.

The committee developed two specific recommendations that focus on policy areas of ongoing concern. These recommendations underscore the importance of mechanisms for ongoing evaluation of effectiveness, including mechanisms either for dynamic policy adjustments or automatic sunsetting.

1.5.1 Reassess policies and requirements for regulatory compliance and reporting and the mechanisms used to ensure safety and financial accountability, with the aim of automating, simplifying, or eliminating those that unduly burden investigators, institutions, and funding agencies. This review should produce procedures for evaluating the impact of the changes and adjusting policies as needed over time.

1.5.2 Reexamine academic and government policies for funding faculty salaries and capital projects. Current NIH policies permit up to almost full coverage of faculty salaries from direct costs and up to full coverage of capital projects from indirect costs. Some have raised concerns that these policies might incentivize universities to seek such funds to hire faculty and construct buildings, even during "stress" times in which maximizing direct funding of research might be more important. All stakeholders should work together to implement a recommendation by the NIH Biomedical Research Workforce Working Group that NIH should "gradually reduce the percentage of funds from all NIH sources that can be used for faculty salary support."[16] At the same time, the federal "contributed effort penalty" must be modified so that institutions are rewarded rather than penalized for paying faculty salaries for time devoted to funded research. Including procedures for formal, ongoing evaluation of the impact of any negotiated changes will be crucial so that both the extent and the pace of the policy adjustments can be fine-tuned as needed.

16 Report of the Biomedical Research Workforce Working Group, a working group of the advisory committee to the NIH Director (National Institutes of Health, June 14, 2012), http://acd.od.nih.gov/biomedical_research_wgreport.pdf.

Goal 2:

Promote cooperative, synergistic interactions among the academic, government, and private sectors throughout the discovery and development process

Creating an interdependent ecosystem requires incentives for basic and applied research, development, and deployment. Novel discoveries can emerge during the development process, and new technologies can arise out of basic research labs. The academic, government, and private sectors must develop an inclusive and adaptive environment that ensures that the unique objectives, skills, and points of view of the different sectors are integrated and optimally utilized.

To take advantage of the potential of transdisciplinary approaches to solve complex problems, academia, government, and industry must develop efficient and effective interfaces that function on both local and global scales. The committee recommends development of policies and practices across these sectors that promote transdisciplinary approaches to scientific and technological problem-solving in individual research laboratories undertaking novel collaborations, in developing novel education and research training regimens, and in establishing shared research centers or large, project-focused teams. The committee's recommendations outline examples of contributions within and between academia, government, and industry that could contribute to the emergence of a more vibrant and innovative research and development ecosystem.

- ### Recommendation 2.1 *(to government)*

  Establish one or more "grand challenges" that will motivate alignment, cooperation, and integration of efforts and approaches across academia, government, and industry. The magnitude and potential impact of these challenges should engage the scientific and engineering communities; inspire the next generation of science, technology, engineering, and mathematics students; and capture the public imagination.

The value of grand challenges lies in their unique ability to focus talent, effort, and resources on an important need and to generate advances that not only address the specific need but develop new capabilities and infrastructure with utility beyond the grand challenge effort itself. The committee believes that a grand challenges program could serve as a catalyst for the emergence of transdisciplinary science and as an experiment to assess new modes of interactions among academia, industry, and government.

To recommend specific grand challenges is beyond the scope of this committee, but several groups have articulated sets of grand challenges for particular sectors (e.g., the Gates Foundation's Grand Challenges in Global Health initiative and the Grand Challenges Initiative of the

White House Office of Science and Technology Policy) and disciplines (e.g., the NAE Grand Challenges for Engineering initiative or the NRC's *Grand Challenges in the Environmental Sciences*). These efforts provide examples of potential grand challenges. The specific grand challenges chosen are less important in the context of this report than the process of involving a large number of stakeholders in a highly public and participatory exercise of identifying challenges.

• Recommendation 2.2 *(to academia, industry, and government)*

Develop and implement new models for research alliances between academia and industry.

American corporations are operating under new constraints, including financial market pressures and increasing international competition (Appendix I considers potential policy revisions specific to international issues). Many corporations are reluctant to adopt long-term horizons or to conduct high-risk in-house basic research, especially when integration across scientific disciplines requires many kinds of expertise. Consequently, industry is increasingly embracing an outsourcing strategy, replacing in-house research with the purchase of intellectual property or of entire companies when early risk has been mitigated. If the "business" of universities is to export knowledge, perhaps a crucial element of the business of industry is now to learn how to import knowledge in the forms of discoveries and technological advances as well as an appropriately trained scientific and technological workforce. A number of barriers impede robust commerce between industry and academia, although some institutions have crafted "master agreements" that establish inter-institutional common ground and thus ease development of project-specific language, and many universities host educational programs designed to promote interactions between academia and the private sector. Successful examples from which we can glean effective practices and consider new ones commonly begin by identifying stakeholder needs and subsequently pursue intellectual property considerations that are transparent and simple. Adoption of the following recommendations, some of which include government participation, would promote improved collaboration between academia and industry:

2.2.1 Create programs, facilitated by tax incentives, through which industry can provide direct support (with funds, materials, equipment) for academic discovery research. For example, the research and development (R&D) tax credit for industry-supported academic research should be increased.

2.2.2 Establish sponsored research programs that fund proposals initiated by academic investigators and refined through joint consultation with industry partners.

2.2.3 Build programs and mechanisms that support collaboration at early (so-called precompetitive) stages of research with little or no negotiation of intellectual property.

• Recommendation 2.3 *(to academia, industry, and government)*

Enhance permeability between industry and academia at all career stages.

Discovery is not a one-time event, and development is not a linear process. Each discovery can uncover gaps in our understanding or suggest new avenues for exploration. Newly developed technologies can enable researchers to ask and answer new questions. Rarely can an academic insight be "exported" to a company and then proceed smoothly through development with no further input from the basic researcher. Programs that train individuals to work in both environments, as well as increased opportunities for short-term exchanges, would promote a smoothly functioning research and development continuum (Appendix II summarizes some examples).

In addition, supporting transdisciplinary and team-based projects requires substantial scientific and technical expertise. Identifying opportunities for, and then managing, joint projects involving individuals from the academic, private, and government sectors requires expert project managers, just as evaluating grant proposals and judging the safety and efficacy of novel therapeutics and products demand refined expertise. Funding agencies must have the resources necessary to attract exceptional scientists and engineers and provide them with enough independence to react flexibly and efficiently to problems and opportunities. Some agencies, such as NSF and DARPA, enlist academic scientists for short-term rotations, while NIH employs permanent staff with extensive research experience. In a truly interdependent innovation ecosystem, funding agencies would serve as integral partners rather than top-down resource providers. The committee recommends the development of academic programs, with participation of all three stakeholder groups, targeted at training individuals for careers in the conception, execution, management, and communication of transdisciplinary science, thus creating a workforce to support a larger transdisciplinary funding portfolio.

2.3.1 Design and institute internship programs for graduate student and postdoctoral trainees that provide hands-on experience with industry-relevant business models and research processes. Federal training-grant mechanisms should include mandates for universities to propose externship programs that allow students to become familiar with career paths, including private industry, science policy and communication, grant and project management, career science positions in core facilities, and other critical options in addition to the traditional academic route.[17]

2.3.2 Develop research alliances and sabbatical programs that encourage and enable industry researchers to work in university labs, and vice versa.

17 Also described in Report of the Biomedical Research Workforce Working Group, a working group of the advisory committee to the NIH Director (National Institutes of Health, June 14, 2012), http://acd.od.nih.gov/biomedical_research_wgreport.pdf.

• Recommendation 2.4 *(to academia and industry)*

Set new priorities for the technology transfer function between academia and industry with the explicit goal of maximizing the exchange of knowledge, resources, and people.

The Bayh-Dole Act of 1980, which endows to universities (rather than the federal government) ownership of intellectual property generated by federally funded research, has helped to energize the U.S. high-technology sector. The act has driven creation of more than 7,200 companies (including nearly 600 in 2010, despite the national recession) and more than 8,800 new products. Academia-inspired start-ups have contributed approximately $190 billion to the U.S. gross national product and have created more than 275,000 jobs over a nine-year period.[18]

While technology transfer offices (TTOs) can serve an important liaison role on campuses, they are less likely to reap substantial financial benefits from licensing and patenting. In 2009, approximately 80 percent of the 149 universities surveyed by the Association of University Technology Managers reported license income of less than $10 million. The 2009 data extend a long trend: only 29 reporting institutions averaged more than $10 million in annual license revenue from 2000 to 2009 (Figure 1). Typically, such revenue came from one or two licenses rather than from a steady flow of modest yields.

The following recommendations aim to ensure that TTOs remain focused on the academic and knowledge transfer missions.

2.4.1 Embed technology transfer activities in innovation-technology-alliance offices whose primary metric of success is knowledge export, not maximization of financial return. Conduct technology transfer activities in active coordination with novel business development and alliance program management, as well as with entrepreneurship education programs.

2.4.2 Streamline intellectual property processes to increase the efficiency of knowledge development and export. This may include development of institutional master template agreements (subject to company- and deal-specific refinements) that can greatly facilitate negotiations.

2.4.3 Ensure all agreements include a provision that unused knowledge becomes public in a timely fashion.

18 Amity Shlaes, "Three Policies That Gave Us the Jobs Economy," *Wall Street Journal*, October 17, 2011, http://online.wsj.com/article/SB10001424052970203914304576628900383779840.html; and http://www.b-d30.org/.

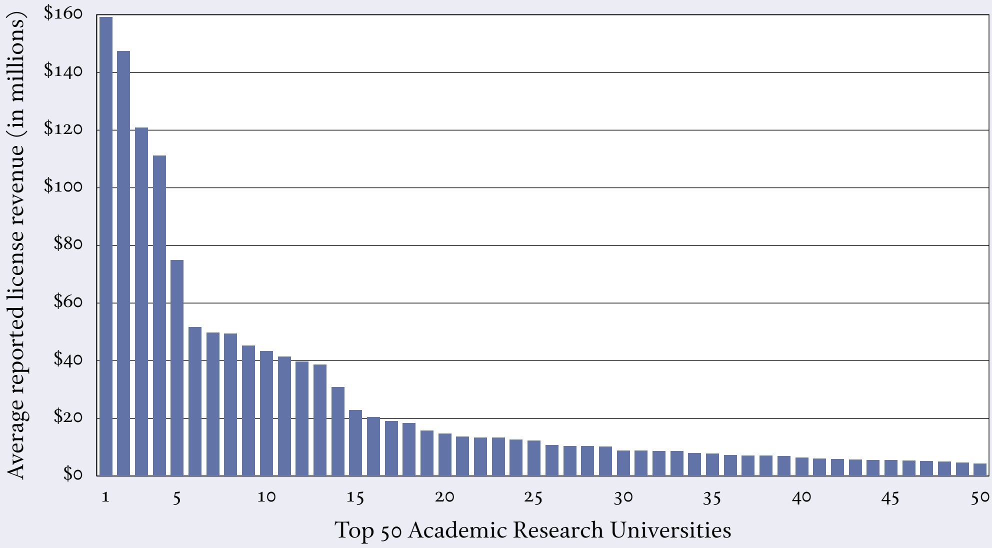


Figure 1. Average Yearly Gross License Revenue for Top 50 Research Universities (2000 – 2009).
Source data: Association of University Technology Managers.

• Recommendation 2.5 *(to academia, industry, and government)*

Develop policies that focus on common interests between academia and industry, while acknowledging and managing intrinsic and avoidable conflicts.

Increasingly complex rules governing conflict of interest are another obstacle to collaboration between industry and academia. To address concerns that academic researchers might allow their research priorities or interpretation of data to be influenced by their ties to industry or their hope of financial gain, universities and the federal government have instituted procedures to monitor academic scientists' relationships with industry. In LSM, preclinical and clinical conflict of interest policies have become exceedingly complex in efforts to eliminate conflict-driven risks to patients. Barriers to collaboration are proliferating at the very time when technological capabilities are advancing rapidly and the potential for trans-sector scientific breakthroughs is greater than ever.

Both academia and industry need to develop a culture that first identifies common interests as they relate to improving the human endeavor and then recognizes, acknowledges, and manages potential conflicts of interest.

2.5.1 Academic institutions should clearly declare their mission and goals for industry alliances and collaborations (Appendix II outlines some successful models) and develop policies that focus on common interests and *recognize* and *manage* potential.

2.5.2 Academic institutions should be required to disclose research relationships between themselves, individuals, and industry partners on the institution's website. Some universities currently conduct this practice, and the committee urges others to follow.

• Recommendation 2.6 *(to government)*

Create mechanisms that increase coordination and cooperation among government agencies that support PSE and LSM.

Scientific research in the United States has long been endowed with an enormous public trust. Opinion polls reveal sustained, strong, and consistent public admiration of scientists and support for scientific research, even at times of severe economic downturn. The federal government has long provided the world's most robust program of support for scientific research, recognizing in particular the essential role of public support for innovative, untargeted basic research—much of which takes place within our academic institutions. A clear demonstration of the enthusiasm of governmental support is the spectrum of federal agencies that help to organize, and then fund generously, programs for scientific research and training. For example, LSM is supported by well over twenty federal agencies.

Unfortunately, this decentralized mode of government funding for research substantially complicates efforts to achieve transdisciplinary integration. Each agency must compete annually for its slice of the federal budget, and even within the LSM sector, funds for the supporting agencies reside in different segments of the federal budget. This competition for resources drives each agency to devise programs that are separate and distinctive from the others, thus minimizing cooperation, and even communication, among programs that are conceptually or technologically overlapping and thus could benefit from integration. As a result, scientific progress is impeded, and the prospects for developing a broad integration across LSM and PSE, and for linking that unified effort to the private sector, are dimmed. The government must devise new programs and policies to incentivize inter-agency coordination of scientific research and development.

2.6.1 Develop mechanisms for agencies to jointly fund infrastructural needs. Specifically, the committee recommends that the National Science and Technology Council establish a coordinating committee to focus on PSE-LSM interagency coordination. In parallel, OMB should require funding agencies to set aside a fraction of their budgets for projects jointly funded by multiple agencies.[19]

2.6.2 Promote transdisciplinary research and training through interagency supported research and training grants.

2.6.3 Agencies that do not traditionally fund projects involving both academic and private sector participants in the DARPA tradition should consider limited pilot programs to explore the possibility that some mission goals might be effectively met by including such approaches in their portfolios.

19 The National Network for Manufacturing Innovation is an example of an initiative that was launched using existing funds from federal agencies and will be sustained through coinvestments by industry partners, state and local agencies, foundations, and the federal government. See http://www.manufacturing.gov/nnmi_overview.html.

Conclusion

Revising policy and practice across the U.S. science and technology enterprise is a daunting task. Because the system is so interconnected, success will require change in many places simultaneously. Each stakeholder addressed by the committee's recommendations likely will recognize that it must accommodate considerable uncertainty or risk. However, the scientific and technological opportunities are enormous, and stakeholders willing to undertake the difficult process of change will reap great benefits. If the current scientific and technological potential can be fulfilled, America's research enterprise will continue to lead the world. Our knowledge and understanding of the universe and ourselves will be expanded in unprecedented ways. Achieving these goals will require new levels of cooperation and integration, as well as updating and reinventing policies and practices across academia, industry, and government. The committee hopes that its recommendations will provide a useful roadmap for encouraging and speeding that process of cooperation and integration.

Appendix I: A Talented International Workforce

Research in science and engineering has been an integral component of U.S. innovation for over a century. In the decades following World War II, many leading scientists, engineers, and inventors immigrated to the United States to pursue uniquely available opportunities. They shared a deep commitment to excellence and leadership, and the nation's prosperity, security, and standard of living flourished. In the twenty-first century, science and engineering research and education have become increasingly competitive global enterprises as countries around the world seek to enhance their scientific and technological influence and realize the social and economic benefits conferred by a strong research system.

To preserve U.S. leadership in science and technology, all sectors of the research enterprise—industry, academia, and government—must come together to examine and strengthen America's place in the global marketplace for talent and expertise. The American Academy of Arts and Sciences' *ARISE II* report offers recommendations to strengthen research connections among these sectors. This appendix to the *ARISE II* report addresses a specific concern confronting the United States today: how to remain competitive and attract the world's scientific talent in the global research ecosystem.

Challenges to Government

Many countries worldwide have embraced a core principle long recognized by the United States: that a strong national investment in advanced science, engineering, education, and technological development is vital to a nation's economic and social well-being.[20] The investments made in scientific research at universities and national laboratories promote economic prosperity through technological innovation, the development of new industries (and subsequent creation of profits and increased tax revenues), and the continuous production of highly skilled workforces that benefit all sectors. These investments also encourage young people to join the workforce and form new companies. Finally, they enhance national security and industrial competitiveness.

Less appreciated are the detrimental effects of erratic immigration policies on a nation's scientific progress. In a mobile and globalized scientific world, countries that offer a dynamic, open, and well-supported science and education enterprises will attract and retain a diverse and talented science workforce. Many countries now recognize this connection and are adjusting their own research investments and immigration policies in ways that enhance their appeal to the international community and the global marketplace.[21] Now, while the future

20 Subra Suresh, "Moving toward Global Science," *Science* 333 (6044) (2011): 802.

21 *Not Coming to America* (The Partnership for a New American Economy and The Partnership for New York City, May 2012), http://www.renewoureconomy.org/sites/all/themes/pnae/not-coming-to-america.pdf.

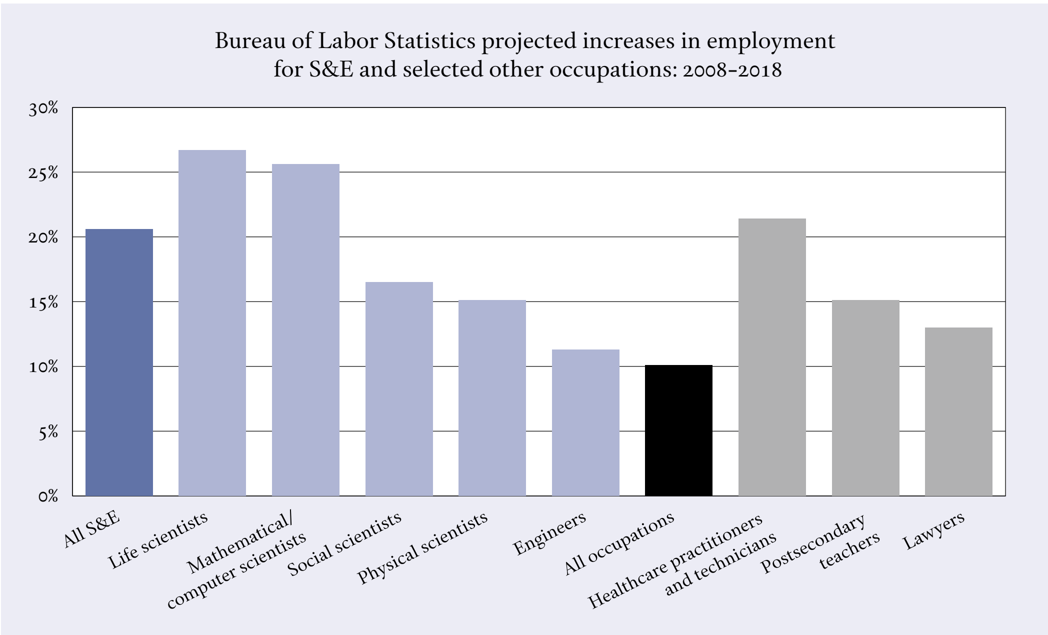


Figure A1: The future of science and engineering occupations.
Source: Adapted from National Science Board, *Science and Engineering Indicators 2012* (Arlington, VA: National Science Foundation, 2012), 3-12, http://www.nsf.gov/statistics/seind12.

appears comparatively promising for employment within the U.S. science and engineering professions (Figure A1), is the time to reconsider visa and immigration policies.

Challenges to Industry

The changing international landscape offers new challenges and opportunities for research and manufacturing as companies establish R&D programs abroad. U.S.-based high-tech manufacturing jobs declined by 28 percent from 2000 to 2010, in part due to the rapid growth of R&D capabilities in Asia.[22] Globalization has affected where research is conducted, how it is funded, and what research is pursued. Moreover, a focus on short-term profits has led many companies to deemphasize long-term research. This is especially evident in PSE, where the private sector—including industrial research labs such as Bell Labs, Xerox PARC, General Electric, IBM, and DuPont—has dramatically decreased the size of its U.S. basic R&D portfolio.

22 National Science Board, *Science and Engineering Indicators 2012*, NSB 12-01 (Arlington, VA: National Science Foundation, 2012).

U.S. multinational corporations increased R&D employment at their foreign affiliates by 94 percent from 2004 to 2009.[23] Companies have many compelling reasons to pursue markets globally (e.g., other countries developing their own R&D workforce, matching manufacturing sites to local R&D sites, and adopting and producing products to match local conditions and uses). Current U.S. tax laws encourage multinational companies to relocate assets and jobs to low-tax foreign countries, in part because U.S. corporate taxes on foreign profits are deferred until profits are repatriated. If the U.S. government incentivizes U.S. corporations to maintain and build their investment in domestic R&D jobs, the resulting impact has the potential to positively influence the nation's public and private R&D sector.

State of Scientific Migration

Highly educated and skilled foreign nationals have contributed to our nation's economic prosperity and preeminent research system, and they complement the highly skilled and educated U.S citizen workforce. From 1973 to 2008, the percentage of foreign-born science and engineering doctorate holders employed in U.S. universities and colleges increased from 12 percent to 25 percent.[24] While the overall trend reveals an influx of foreign-born researchers, other indicators of the foreign-born workforce reveal a more nuanced shift. From 1989 to 2009 the number of temporary work visas issued to highly skilled workers increased (Figure A2), with two notable anomalies.[25] The first appears in the years following the September 11 attacks in 2001, when foreign-born nationals began to experience difficulty securing visas to the United States. While this trend lasted a few years, the second decline in issued visas occurred with the collapse of the U.S. economy after 2008. This latest trend might be reversing, as demonstrated by the increase in the number of visas issued. But that shift might also be a temporary reflection of near-term global economic conditions. Another indicator is the intent of foreign-born science and engineering doctorate holders to stay in the United States. Since 1999, the number of foreign-born recipients with U.S. science and engineering doctorates who intended to stay in the United States after graduation generally increased. However, beginning in 2007, this number began to decline, in part because their home countries created and expanded their own competitive research, education, and industrial enterprises and career opportunities (Figure A2).

The United States must reshape its policies that address foreign-born scholars and researchers. Failure to do so will place this country at a severe disadvantage in the international competition for talented scientists, engineers, and intellectual leaders and will put it at risk for

23 National Science Board, *Science and Engineering Indicators 2012,* chap. 3.

24 National Science Board, *Science and Engineering Indicators 2012*.

25 Ibid.

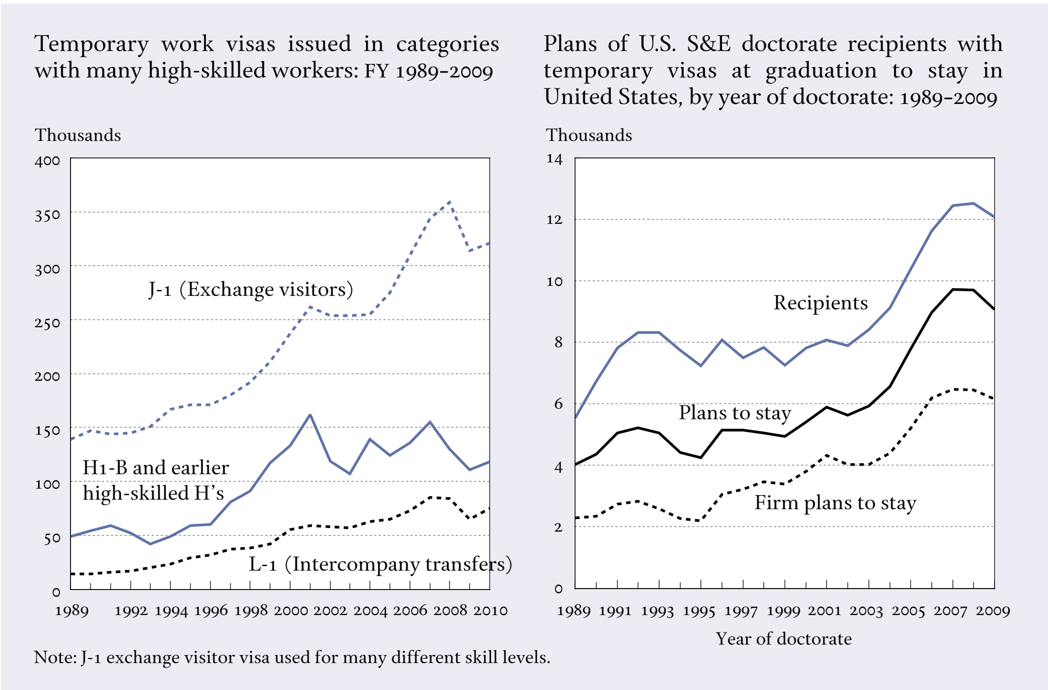


Figure A2: Stay rates of U.S. science and engineering doctoral recipients.
Source: Reprinted from National Science Board, *Science and Engineering Indicators 2012* (Arlington, VA: National Science Foundation, 2012), 3-50, 3-52, http://www.nsf.gov/statistics/seind12/.

an even greater shortage of the educated workers needed for public and private knowledge-intensive jobs, including in the research and development and high-tech manufacturing sectors. American companies would risk declines in productivity and innovation. Entrepreneurs, who seek to commercialize innovations resulting from American research investments, might launch and expand more companies outside the United States. Highly educated and skilled foreign nationals have contributed to our nation's economic prosperity and preeminent research system for generations, and they complement the highly skilled and educated domestic workforce.

For decades, foreign graduate students sought advanced education and research training in the United States; many stayed. Today, "American" corporations are increasingly multinational. These two factors suggest that sustained U.S. leadership in the global research ecosystem will require policies that encourage greater investment in intellectual and human capital throughout the world. The committee strongly supports two revisions to current policy that will help ensure that the U.S. science enterprise remains at the forefront of research for decades to come.

First, the federal government should create incentives that (a) attract international researchers to the United States for education and training and (b) enhance their ability to remain in the United States after they complete their training.

The U.S. government should streamline immigration policies and procedures to enable our country to attract, retain, and benefit from outstanding international students and graduates. The current employment-based visa process is overly restrictive; it suffers from inappropriate quotas and an unsatisfactory approval process. In addition to streamlining the immigration process for talented students, the United States must also encourage highly educated and gifted U.S.-trained foreign professionals in areas of critical need to join and advance the R&D sector of our national economy. Post-study work opportunities should be created for exceptional recent Ph.D. graduates, many of whom are trained in the cutting edge of their fields.

In a recent global survey of scientific migration, the opportunity to improve one's career prospects was cited as a top factor in deciding to work abroad.[26] A powerful incentive to ensure that researchers come to the United States and stay, therefore, is a competitive system for advancement, including commitments to attract and equip early career scientists with the tools they need to succeed professionally. In 2008 the Academy's *ARISE I* report highlighted recommendations that support early career faculty and encourage high-risk, high-reward, and potentially transformative research—important incentives for recent international graduates.[27] Federal agencies have made encouraging progress toward implementing these recommendations, but more could be done.

Second, the federal government should strengthen incentives for corporations to develop and maintain high-tech jobs, including R&D jobs, in the United States.

We have an opportunity to reshape the competitive environment of multinational science and engineering companies. A reformed and simplified tax system is needed to match the U.S. marginal corporate tax rate with rates in other Organisation for Economic Co-operation and Development countries. To allow for longer-term planning, the Research and Experimentation tax credit should be permanently extended. Incentivizing corporations to maintain and build their investments in domestic R&D jobs would stimulate the growth of the nation's

26 R. Van Noorden, "Global Mobility: Science on the Move," *Nature* 490 (2012): 326–329.

27 American Academy of Arts and Sciences, *ARISE—Advancing Research In Science and Engineering: Investing in Early-Career Scientists and High-Risk, High-Reward Research* (Cambridge, MA: American Academy of Arts and Sciences, 2008), http://www.amacad.org/arisefolder/ariseReport.pdf.

public and private R&D sector. The committee endorses the tax policy improvements recommended by the President's Council of Advisors on Science and Technology in a recent report to President Obama.[28]

Progress in scientific, technological, and medical research is increasingly spread across the global arena. Although the United States remains the largest single contributor to this progress, China and Japan have emerged as the second and third most productive countries for R&D as measured by total gross domestic expenditures for R&D.[29] As these and other countries compete as never before to realize the social and economic benefits conferred by a strong national research system, the United States must reconsider its visa and immigration policies to enhance our nation's competitiveness in the international community and the global marketplace.

28 President's Council of Advisors on Science and Technology, *Report to the President on Ensuring American Leadership in Advanced Manufacturing* (Washington, DC: The White House, 2011), http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-advanced-manufacturing-june2011.pdf.

29 National Science Board, *Science and Engineering Indicators 2012,* chap. 4.

Appendix II: Examples of Programs that Align with the Goals of this Report

Transdisciplinary Training Programs

- Launched in 1997, the Integrative Graduate Education and Research Traineeship (IGERT) is an NSF-wide endeavor involving the Directorates for Biological Sciences (BIO), Computer and Information Science and Engineering (CISE), Education and Human Resources (EHR), Engineering (ENG), Geosciences (GEO), Mathematical and Physical Sciences (MPS), Social, Behavioral, and Economic Sciences (SBE), the Office of Polar Programs (OPP), and the Office of International Science and Engineering (INT). The IGERT program was developed to meet the challenges of educating U.S. Ph.D. scientists, engineers, and educators with interdisciplinary backgrounds to become leaders and creative agents for change. The program is intended to catalyze a cultural change in graduate education—for students, faculty, and institutions—by establishing innovative new models for graduate education and training in a fertile environment for collaborative research that transcends traditional disciplinary boundaries. IGERT is also intended 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 Semiconductor Research Consortium (SRC) supports enhanced education of students through participation in industry-relevant research, as well as interaction with industry scientists and engineers. The SRC approach helps to produce top caliber graduates who "hit the ground running" and rapidly contribute to innovation and advances within the organization/industry.
- A recent proposal by the National Institute of General Medical Sciences, *Strategic Plan for Training and Career Development*,[30] offers a promising pathway to improve the skills of trainees by increasing their exposure to the industrial R&D process, concepts, and practices. Such well-managed university-industry partnerships can increase the efficiency of the innovation system by providing the nation's future workers with valuable and directly applicable experiences during their postgraduate, graduate, and even undergraduate training. Arguably, even students who pursue careers in academia, policy, or writing will gain beneficial collaborative experiences and an appreciation for the complexity of the innovation system.

30 National Institute of General Medical Sciences, *Strategic Plan for Training and Career Development* (Ripple Effect Communications, 2010), http://publications.nigms.nih.gov/training/Training_Strategic_Plan_Summary.pdf.

- Many schools have developed programs that support a transdisciplinary training approach. A few examples include:
  - The biomedical science graduate programs at the University of Washington, http://www.uwmedicine.org/research/biomedical-and-life-sciences/pages/biomedical-science-graduate-programs.aspx
  - The Interdisciplinary Quantitative Biology program at the University of Colorado, http://biofrontiers.colorado.edu/education/iq-biology/
  - The Biomedical Sciences (BMS) Program, at the University of California, San Francisco, http://bms.ucsf.edu/
  - The Ecological Sciences and Engineering Interdisciplinary Graduate Program at Purdue University, http://www.purdue.edu/discoverypark/ese/index.php.

Public-Private Partnerships

Structural Genomics Consortium (SGC)

- SGC is an Anglo-Canadian-Swedish not-for-profit organization that aims to determine the three-dimensional structures of proteins of medical relevance and to place them in the public domain without restriction. SGC focuses on proteins that would not normally be funded by industry or academia.

- SGC is funded by multiple organizations: the Wellcome Trust, the Canadian Institutes of Health Research, the Ontario Ministry of Research and Innovation, Novartis, Pfizer, Eli Lilly Canada, GlaxoSmithKline, and Abbot. SGC currently has more than 250 collaborations with universities in 19 countries worldwide.

Energy Biosciences Institute (EBI):

- EBI is a unique collaboration between British Petroleum (BP) and the University of California, Berkeley; the Lawrence Berkeley National Laboratory; and the University of Illinois at Urbana-Champaign. BP supports the institute with a ten-year, $500 million grant to conduct R&D dedicated to the new field of energy bioscience, focusing on the development of next-generation biofuels as well as various applications of biology to the energy sector.

- By partnering with academia to explore an area in which BP had few internal experts (e.g., biologists), BP was able to enter a completely new enterprise without having to create a new company division.

- Use-inspired basic research approach—the research preproposals are reviewed by an executive committee of senior academics and BP engineers to ensure that the research is done with full knowledge of what is needed by the corporation, followed by an external peer-review process.

- The intellectual property negotiations were nontrivial, and outside counsel was needed to assist the university in handling the negotiations. Very generally: BP owns the intellectual property for research conducted purely by BP; the universities own the intellectual property for research conducted purely by university faculty.

Semiconductor Research Corporation (SRC)

- SRC was established in 1982 as a consortium of U.S. semiconductor companies to fund and manage university research with the aim of defining relevant research directions; exploring potentially important new technologies; and generating a pool of experienced faculty and highly trained students.
- By joining an SRC program (for a fee based on company revenue), companies gain access to hundreds of millions of dollars in research. Research needs are defined through a consensus-based process with industry participation.

ARISE II Committee Biographies

Venkatesh (Venky) Narayanamurti (*Cochair*) is Benjamin Peirce Professor of Technology and Public Policy and Professor of Physics at Harvard University. He is also the Director of the Science, Technology, and Public Policy Program at the Belfer Center for Science and International Affairs at the Harvard Kennedy School. He currently serves as the Foreign Secretary of the U.S National Academy of Engineering. He was formerly the John L. Armstrong Professor and Founding Dean of the School of Engineering and Applied Sciences and Dean of Physical Sciences at Harvard University. Previously he served as the Richard A. Auhll Professor and Dean of Engineering at the University of California, Santa Barbara. Before that he was Vice President of Research at Sandia National Laboratories and Director of Solid State Electronics Research at Bell Laboratories. He is an elected Member of the National Academy of Engineering and the Royal Swedish Academy of Engineering Sciences, and a Fellow of the American Physical Society, the American Association for the Advancement of Science, the IEEE, and the Indian Academy of Sciences. He has served on numerous advisory boards for the federal government, research universities, and industry. He is the author of more than 230 scientific papers in different areas of condensed matter and applied physics. He lectures widely on solid state, computer, and communication technologies, and on the management of science, technology, and public policy. He is a Fellow of the American Academy of Arts and Sciences.

Keith R. Yamamoto (*Cochair*) is Vice Chancellor for Research, Executive Vice Dean of the School of Medicine, and Professor of Cellular and Molecular Pharmacology at the University of California, San Francisco. His research is focused on signaling and transcriptional regulation by nuclear receptors, which mediate the actions of several classes of essential hormones and cellular signals; he uses mechanistic and systems approaches to pursue these problems in pure molecules, cells, and whole organisms. He has led or served on numerous national committees focused on public and scientific policy, public understanding and support of biological research, and science education. He chairs the Coalition for the Life Sciences and recently joined the National Academy of Sciences Division of Earth and Life Studies Advisory Committee after completing six years as Chair of that body's Board on Life Sciences. He has been deeply involved in the process of peer review and the policies that govern it at the National Institutes of Health, and presently serves on the Center for Scientific Review Advisory Council. He is a member of the advisory board for the Lawrence Berkeley National Laboratory and is on the Research!America board of directors. He also serves as an advisor to Burrill & Company. He is a Member of the National Academy of Sciences, the Institute of Medicine of the National Academies, and the American Academy of Microbiology. He is a Fellow of the American Association for the Advancement of Science and the American Academy of Arts and Sciences.

Nancy C. Andrews is Dean of Duke University School of Medicine and Vice Chancellor for Academic Affairs. She is also a Professor in the Department of Pediatrics and the Department of Pharmacology and Cancer Biology. She has served as the George Richards Minot Professor of Pediatrics at Harvard University, senior associate in medicine at the Children's Hospital Boston, and a distinguished physician of the Dana-Farber Cancer Institute. She was the Director of the Harvard-MIT MD-PhD program from 1999 to 2003 and Dean for Basic Sciences and Graduate Studies at Harvard Medical School from 2003 to 2007. She maintains an active NIH-funded research laboratory studying mouse models of human diseases. She was a Howard Hughes Medical Institute Investigator from 1993 to 2006. She is the past President of the American Society of Clinical Investigation, a Member of the Institute of Medicine of the National Academies, and a Fellow of the American Academy of Arts and Sciences.

Dennis A. Ausiello is Jackson Distinguished Professor of Clinical Medicine and Director, Emeritus of the MD-PhD Program at Harvard Medical School; and Chairman of Medicine, Emeritus and Director of the Center for Assessment Technology and Continuous Health (CATCH) at the Massachusetts General Hospital. He has made substantial contributions to the knowledge of epithelial biology in the areas of membrane protein trafficking, ion channel regulation, and signal transduction. He has published numerous articles, book chapters, and textbooks and served as an editor of *Cecil's Textbook of Medicine*. His writings have been published in *The New York Times*, *The Wall Street Journal*, *The Boston Globe,* and elsewhere on topics concerning medical education and biomedical research, including human genetics, clinical trials, the inquisitive physician, and the relationship between academic medicine and the private sector. He also serves in a variety of advisory roles beyond his academic affiliations, including his service on the Board of Directors of pharmaceutical company Pfizer Inc., drug-delivery company, TARIS, and interference RNA company, Alnylam. He is a Member of the Institute of Medicine of the National Academies. He is a Fellow of the American Academy of Arts and Sciences.

Lawrence S. Bacow is President Emeritus of Tufts University. He served as President of Tufts University from 2001 to 2011. Prior to assuming the presidency of Tufts, he spent 24 years on the faculty at the Massachusetts Institute of Technology, where he was the Lee and Geraldine Martin Professor of Environmental Studies. He also served as the Chairman of the MIT Faculty and as Chancellor, one of the two most senior academic leadership positions at MIT. Currently he serves as the President in Residence at the Harvard Graduate School of Education, Senior Adviser to ITHAKA S+R, and as a Member of the Harvard Corporation. His current research focuses on the relationship between technology and productivity in higher education. He is a Fellow of the American Academy of Arts and Sciences.

Malcolm R. Beasley is Theodore and Sydney Rosenberg Professor of Applied Physics Emeritus at Stanford University. His research interests include condensed matter and materials physics; superconductivity and superconducting materials; transport studies of novel materials; applications of superconductivity; nonlinear dynamics; and advanced approaches to thin film deposition. From 1998 to 2001, he served as Dean of the School of Humanities and Sciences at Stanford University. He was the Director of the Geballe Laboratory for Advanced Materials from 2003 to 2005. He is a Member of the American Physical Society, the IEEE, the Materials Research Society, and the National Academy of Sciences. He is presently President-Elect of the American Physical Society and Chair of the Board of Associated Universities, Inc., a NGO that oversees scientific facilities for the federal government. He is a Fellow of the American Association for the Advancement of Science and the American Academy of Arts and Sciences.

Edward J. Benz, Jr. has been President and Chief Executive Officer of Dana-Farber Cancer Institute since 2000. He also serves as President and Chief Executive Officer of Dana-Farber/Partners CancerCare, as a Director of Dana-Farber/Harvard Cancer Center, and as a trustee of Dana-Farber/Children's Hospital Cancer Center. He is presently the Richard and Susan Smith Professor of Medicine, a Professor of Pediatrics, and a Professor of Genetics at Harvard Medical School, where he received the Soma Weiss and Leon Resnick Awards for Research. Immediately prior to assuming the presidency of Dana-Farber Cancer Institute, he was Chairman of the Department of Medicine at the Johns Hopkins University School of Medicine and the Sir William Osler Professor of Medicine. He is a Member of the Institute of Medicine of the National Academies. He is past President of the American Clinical and Climatological Association, the Association of American Cancer Institutes, American Society of Hematology, the American Society of Clinical Investigation, and a previous cochair of the NIH Advisory Board for its Clinical Research Center. Most recently, he received the annual Mentorship Award from the American Society of Hematology and the Margaret Kripke Legends in Medicine Award for Advancing the Careers of Women in Cancer Medicine. He is an Associate Editor of the *New England Journal of Medicine* and coauthor of three textbooks. He is an internationally recognized hematologist and an expert in inherited anemias and red cell diseases. He is a Fellow of the American Academy of Arts and Sciences.

Leslie C. Berlowitz is President of the American Academy of Arts and Sciences. She also holds the William T. Golden Chair at the Academy. She is responsible for the intellectual vision and day-to-day management of the Academy and oversees its research areas in science, engineering, and technology; global security and energy; the humanities, arts, and education; and American institutions and the public good. She has established two residential fellowship programs for young scholars at the Academy: the Hellman Fellowship in Science and Technology Policy and the Visiting Scholars Program. She was a member of the committee that prepared the Academy's 2008 report, *ARISE: Advancing Research In Science and Engineering: Investing in Early-Career Scientists and High-Risk, High-Reward Research*. Before joining the Academy in 1996, she was Vice President at New York University. She is a Fellow of the American Academy of Arts and Sciences.

David Botstein is Director of the Lewis-Sigler Institute for Integrative Genomics and Anthony B. Evnin Professor of Genomics at Princeton University. Prior to joining Princeton University, he served as the Chairman of the Department of Genetics at Stanford University's Medical School. In 1987, he joined Genentech as the Vice President for Science. His research has centered on genetics, especially the use of genetic methods to understand biological functions. His current research effort is devoted to the study of yeast biology at the system level. At Princeton, he is leading a team of faculty who are teaching a new experimental introductory science curriculum, where the basic ideas of physics, chemistry, computer science, and biology, along with the relevant mathematics, are taught together. He is a Member of the National Academy of Sciences and the Institute of Medicine of the National Academies. He is a Fellow of the American Academy of Arts and Sciences.

Kim Bottomly is President of Wellesley College. She was previously Deputy Provost at Yale University, where she was a faculty member for 27 years. An immunobiologist, she was a member of the Immunobiology Study Section at the National Institutes of Health and the Advisory Council of the National Institute of Allergy and Infectious Diseases. She received a National Institutes of Health MERIT award and was Editor of the journal *Immunity*. In 2008, the University of Washington named her one of their "Wondrous 100," the school's top alumni of the past century. An elected member of the Connecticut Academy of Science and Engineering, she serves on the Yale School of Engineering and Applied Science Leadership Council, the Olin College of Engineering President's Council, the Teach for America Champions' Board, and the WGBH Board of Trustees. She received a 2012 Catalyst Award from the Science Club for Girls in Cambridge, Massachusetts. She is a Fellow of the American Academy of Arts and Sciences.

Robert A. Brown is President of Boston University. At Boston University, he has worked to strengthen the central importance of the teaching and research functions of the University. He served on the President's Council of Advisors on Science and Technology from 2006 to 2008, and currently is a Director of the DuPont Company and a Trustee of the Universities Research Association. He also is Chairman of the Academic Research Council of the Ministry of Education of the Republic of Singapore, and serves on the Research Innovation and Enterprise Council, chaired by the Prime Minister. In 2006, he was named an honorary citizen: the highest form of recognition given by the government to any non-Singaporean. Prior to his appointment at Boston University, he was Provost from 1998 to 2005 and Warren K. Lewis Professor of Chemical Engineering at the Massachusetts Institute of Technology. He has published over 250 papers in areas related to mathematical modeling of transport phenomena in materials. He is a Member of the National Academy of Engineering and the National Academy of Sciences. He is a Fellow of the American Academy of Arts and Sciences.

Claude R. Canizares is Vice President and the Bruno Rossi Professor of Physics at the Massachusetts Institute of Technology. He has responsibility for MIT's major international partnerships and oversees the MIT Lincoln Laboratory. He came to MIT as a postdoctoral fellow in 1971 and joined the faculty in 1974. He has served as Director of the Center for Space Research (1990 to 2001), Associate Provost (2001 to 2006), and most recently as Vice President for Research & Associate Provost (2006 to 2013). He is a principal investigator on NASA's Chandra X-ray Observatory. He has also worked on several other space astronomy missions and is the author or co-author of more than 230 scientific papers. His service outside MIT includes the Department of Commerce's National Advisory Council on Innovation and Entrepreneurship and the Emerging Technology and Research Advisory Committee and the National Research Council's (NRC) Committee on Science, Technology and the Law. He served as Chair of the NRC's Space Studies Board and was a member of the NASA Advisory Council and the Air Force Scientific Advisory Board, among others. He has received several awards, including decoration for Meritorious Civilian Service to the United States Air Force, and two NASA Public Service Medals. He is a Member of the L-3 Communications, Inc. Board of Directors. He is a Member of the National Academy of Sciences and the International Academy of Astronautics and is a Fellow of the American Physical Society and the American Association for the Advancement of Science. He is a Fellow of the American Academy of Arts and Sciences.

Uma Chowdhry is Chief Science and Technology Officer, Emeritus of DuPont. She joined DuPont in 1977 and later rose to become the first woman to hold a Chief Science and Technology Officer position in a Fortune 50 chemical and materials company. Her early work at DuPont focused on developing battery materials and heterogeneous catalysts for making various chemical processes. Her research interests broadened to include electronic packaging materials, including ceramics. In 1987, she led DuPont's research effort in ceramic superconducting materials and developed a world class program that generated over 20 patents and 50 publications. She subsequently held a number of research and business management positions with the company, integrating research and business planning and helping to improve the transfer of technologies from laboratory to market. In 1995, she was appointed Business Director of DuPont's Terathane® business, which provided chemical intermediates for Lycra® and in January 1999 became Director of DuPont Engineering Technology. She served as Vice President of Central R&D in 2002 and became Senior Vice President and Chief Science and Technology Officer in 2006. She has served on many advisory boards of universities, research institutes, as well as National Academy and Department of Energy committees. She is a member of the National Academy of Engineering, a Fellow of the American Ceramic Society, and a Member of the Delaware Women's Hall of Fame. She is currently on the Board of Directors of Baxter International Inc., and the LORD Corporation, and is cochair of GUIRR, sponsored by the National Academies. She also serves on visiting advisory committees to NIST, Sandia National Labs, MIT Corporation, and Ceramatec Inc. She is a Fellow of the American Academy of Arts and Sciences,

Mary Sue Coleman is President of the University of Michigan. At the University, she holds appointments as Professor of Biological Chemistry in the Medical School and Professor of Chemistry in the College of Literature, Science, and the Arts. A biochemist, her research focuses on the immune system and malignancies. For nineteen years, she was a member of the biochemistry faculty at the University of Kentucky. She has held administrative appointments at the University of North Carolina at Chapel Hill and the University of New Mexico, where she served as Provost and Vice President for Academic Affairs. From 1995 to 2002, she was President of the University of Iowa. She has served on the Association of American Universities Executive Committee, the Internet2 Board of Directors, the National Collegiate Athletic Association Board of Directors, and the Knight Commission on Intercollegiate Athletics. She is a member of the Business Leaders for Michigan Board of Directors; the Presidents Council of the State Universities of Michigan; and the Michigan Strategic Economic Investment and Commercialization Board. She is a trustee of the Gerald R. Ford Foundation. She serves on the boards of directors of Johnson & Johnson and the Meredith Corporation. She is a Member of the Institute of Medicine of the National Academies and a Fellow of the American Association for the Advancement of Science. She is a Fellow of the American Academy of Arts and Sciences.

Alan Ezekowitz is Co-Founder, President, and Chief Executive Officer of Abide Therapeutics; and Entrepreneur-in-Residence of Cardinal Partners. He co-founded Abide Therapeutics with Professors Dale Boger and Ben Cravatt from the Scripps Research Institute in 2011. He was previously Senior Vice President and Franchise Head for Bone, Respiratory, Immunology, and Endocrine at Merck Research Laboratories; he joined Merck in 2006 and retired in March 2011. At Merck, he was responsible for the overall scientific direction of the drug discovery and development process for Merck's key therapeutic areas of immunology, respiratory disease, and endocrine disorders. Prior to joining Merck & Co, Inc. he served as the Chief of Pediatrics at MassGeneral Hospital for Children in 2000, and, in 2001, as Chief of Pediatrics for Partners HealthCare System. He was Chairman of the Executive Committee on Research that oversees research at Massachusetts General Hospital and also served on the Board of Directors of Partners HealthCare System, Inc. In addition, he held positions as Chairman of the Scientific Advisory Board of Anika Therapeutics and was on the Scientific Advisory Board of EntoMed, Cubist Pharmaceuticals, Arris Pharmaceuticals, and the Codman Company. He also consulted for Arthur D. Little, Genentech, and Bristol-Myers Squibb. In 2008, he was honored with the establishment of the R. Alan Ezekowitz Professorship in Pediatrics at the Harvard Medical School. Prior to joining the staff of Mass General in 1995, he served on the staff of Children's Hospital in Boston for eleven years.

Harvey Fineberg is President of the Institute of Medicine of the National Academies. He served as Provost of Harvard University from 1997 to 2001, following thirteen years as Dean of the Harvard School of Public Health. He has devoted most of his academic career to the fields of health policy and medical decision-making. His past research has focused on the process of policy development and implementation, assessment of medical technology, evaluation and use of vaccines, and dissemination of medical innovations. He helped found and served as President of the Society for Medical Decision Making and also served as a consultant to the World Health Organization. At the Institute of Medicine, he has chaired and served on a number of panels dealing with health policy issues, ranging from AIDS to new medical technology. He also served as a member of the Public Health Council of Massachusetts from 1976 to 1979, as Chairman of the Health Care Technology Study Section of the National Center for Health Services Research from 1982 to 1985, and as President of the Association of Schools of Public Health from 1995 to 1996. He is the co-author of *Clinical Decision Analysis*, *Innovators in Physician Education*, and *The Swine Flu Affair*. He has co-edited books on AIDS prevention, vaccine safety, and understanding risk in society. He is the recipient of several prizes, including the Frank A. Calderone Prize in Public Health (2011) and the Henry G. Friesen International Prize in Health Research (2013). He is a Fellow of the American Academy of Arts and Sciences.

Mary L. Good is Dean Emeritus and Special Assistant to the Chancellor of the University of Arkansas at Little Rock. She has held many positions in academia, industry, and government, including President of the American Association for the Advancement of Science (AAAS). In 2004, she was the recipient of the National Science Foundation's highest honor, the Vannevar Bush Award. She was the first female winner of the AAAS's prestigious Philip Hogue Abelson Prize for outstanding achievements in education, research and development management, and public service, spanning the academic, industrial, and government sectors. A recipient of the National Science Foundation Distinguished Service medal and the American Chemical Society Priestly Medal, she is also the 6th Annual Heinz Award Winner. During the terms of Presidents Carter and Reagan, she served on the National Science Board and was Chair of the National Science Board from 1988 to 1991. In addition, she was the Undersecretary for Technology in the U.S. Department of Commerce and Technology during President Clinton's first term. She is a Fellow of the American Academy of Arts and Sciences.

Leah Jamieson is John A. Edwardson Dean of the College of Engineering, Ransburg Distinguished Professor of Electrical and Computer Engineering, and Professor of Engineering Education at Purdue University. In 2007, she served as President and Chief Executive Officer of the

Institute of Electrical and Electronics Engineers (IEEE). She is co-founder and past director of the EPICS (Engineering Projects in Community Service) Program. Her research has focused on speech analysis and recognition; the design and analysis of parallel processing algorithms; and the application of parallel processing to digital speech, image, and signal processing. She was an inaugural recipient of the National Science Foundation Director's Award for Distinguished Teaching Scholars and has been recognized with the IEEE Education Society's 2000 Harriet B. Rigas "Outstanding Woman Engineering Educator" Award and the Anita Borg Institute's 2007 "Women of Vision Award for Social Impact." She was named 2002 Indiana Professor of the Year by the Carnegie Foundation. She was awarded with colleagues Edward Coyle and William Oakes the 2005 NAE Bernard M. Gordon Prize for Innovation in Engineering and Technology Education for the creation and dissemination of EPICS. She is a member of the National Academy of Engineering and a Fellow of the IEEE and the American Society for Engineering Education. She is a Fellow of the American Academy of Arts and Sciences.

Linda Katehi is Chancellor of the University of California, Davis. A Member of the National Academy of Engineering, she chaired the President's Committee for the National Medal of Science and the Secretary of Commerce's Committee for the National Medal of Technology and Innovation. Previously, she served as Provost and Vice Chancellor for Academic Affairs at the University of Illinois at Urbana-Champaign; the John A. Edwardson Dean of Engineering and Professor of Electrical and Computer Engineering at Purdue University; and Associate Dean for Academic Affairs and Graduate Education in the College of Engineering and Professor of Electrical Engineering and Computer Science at the University of Michigan. Her research pioneered the development of on-wafer integration techniques that have led to low-cost, high-performance integrated circuits for radar, satellite, and wireless applications. She was a member of the committee that prepared the Academy's 2008 report, *ARISE: Advancing Research In Science and Engineering: Investing in Early-Career Scientists and High-Risk, High-Reward Research*. She is a Fellow and Board Member of the American Association for the Advancement of Science, a Member of the National Academy of Sciences Committee on the Integrity of Research Data, a Board Member of the EU Cyprus Institute, a Fellow of the Institute of Electrical and Electronics Engineers, and a Member of Sigma Xi. She is a Fellow of the American Academy of Arts and Sciences.

Neal Lane is Malcolm Gillis University Professor at Rice University. He also holds appointments as Senior Fellow of the James A. Baker III Institute for Public Policy, where he is engaged in matters of science and technology policy, and as a Professor in the Department of Physics and Astronomy. He previously served as Provost at Rice University and as Chancellor of the University of Colorado at Colorado Springs. In addition, he was Assistant to the President for Science and Technology and Director of the White House Office of Science and Technology Policy from August 1998 to January 2001. He also served as Director of the National

Science Foundation and member (*ex officio*) of the National Science Board from October 1993 to August 1998. He was a member of the committee that prepared the Academy's 2008 report, *ARISE: Advancing Research In Science and Engineering: Investing in Early-Career Scientists and High-Risk, High-Reward Research*. He is a Fellow of the American Academy of Arts and Sciences and serves as the Vice Chair of the Academy's Council.

Eugene H. Levy is Andrew Hays Buchanan Professor of Astrophysics in the Department of Physics and Astronomy at Rice University. He served as the Howard R. Hughes Provost at Rice University from 2000 to 2010. His research interest in theoretical cosmic physics is aimed at elucidating mechanisms and processes that underlie physical phenomena in planetary and astrophysical systems. Prior to his appointments at Rice, he held several positions at the University of Arizona. From 1983 to 1994, he served as the Head of the Planetary Sciences Department and Director of the Lunar and Planetary Laboratory. Subsequently, from 1993 to 2000, he served as Dean of the College of Science. He was also a member of the faculties of the Applied Mathematics and Theoretical Astrophysics programs. In 1989, he established the NASA/Arizona Space Grant College Consortium and served as its Director for eleven years. He was also a Distinguished Visiting Scientist at the Jet Propulsion Laboratory of the California Institute of Technology from 1985 to 1991. He is a recipient of the NASA Distinguished Public Service Medal and an Alexander von Humboldt-Stiftung Senior Scientist Award. He has served as a Member of the Space Telescope Institute Council, the NASA Advisory Council, the NRC Space Science Board, and as Chair of the Committee on Planetary and Lunar Exploration. He currently serves as a Member (and immediate past Chair) of the Board of Trustees of Associated Universities, Inc. He is a Member of the Science Committee of the NASA Advisory Council and Chair of the Planetary Protection Subcommittee. He is a Fellow and Member of the Council of the American Association for the Advancement of Science.

Joseph B. Martin is Edward R. and Anne G. Lefler Professor of Neurobiology at Harvard Medical School. He served as Dean of the Harvard Faculty of Medicine from 1997 to 2007. Throughout his academic career he has played a key role in establishing numerous collaborative research centers, including the National Institute of Health sponsored Huntington Disease Center Without Walls, the Massachusetts Alzheimer's Disease Research Center, the Dana-Farber/Harvard Cancer Center, and the Harvard Center for Neurodegeneration and Repair. Prior to returning to the Harvard Medical School in 1997 he served first as Dean of the School of Medicine at the University of California, San Francisco (UCSF), and then as Chancellor of UCSF. He is a Member of the Institute of Medicine of the National Academies (IOM) and chaired the IOM's Committee that led to the development of the Human Brain mapping initiative. He was also a Member of the Council of the IOM, concluding two terms in 2002. He is a Member of the American Association of Physicians and a Member and past President of the American Neurological Association. He was awarded the AAMC Abraham Flexner Award in 1999 and has received numerous other national and international distinctions throughout his career. He is a Fellow of the American Academy of Arts and Sciences.

Cherry A. Murray is Dean of the School of Engineering and Applied Sciences (SEAS) at Harvard University. She also holds the John A. and Elizabeth S. Armstrong Professorship of Engineering and Applied Sciences. Previously, she served as Principal Associate Director for Science and Technology at Lawrence Livermore National Laboratory. Before joining Lawrence Livermore in 2004, she served as Senior Vice President for Physical Sciences and Wireless Research at Bell Laboratories. Her research interests include light scattering, soft condensed matter, and complex fluids. In 1989, she received the American Physical Society's (APS) Maria Goeppert-Mayer Award for outstanding achievement by a woman physicist in the early years of her career, and in 2005, she was awarded APS's George E. Pake Prize in recognition of outstanding work combining original research accomplishments with leadership and development in industry. In 2002, *Discover* Magazine named her one of the "50 Most Important Women in Science." She served as President of the American Physical Society in 2009. She is a Member of the National Academy of Sciences and the National Academy of Engineering. She is a Fellow of the American Academy of Arts and Sciences.

Gilbert S. Omenn is Professor of Computational Medicine & Bioinformatics, Internal Medicine, Human Genetics, and Public Health at the University of Michigan. He served as Executive Vice President for Medical Affairs and as Chief Executive Officer of the University of Michigan Health System from 1997 to 2002. He was formerly Dean of the School of Public Health and Professor of Medicine and Environmental Health at the University of Washington. His research interests include cancer proteomics, chemoprevention of cancers, public health genetics, science-based risk analysis, and health policy. He served as Associate Director of the Office of Science and Technology Policy and as Associate Director of the Office of Management and Budget in the Executive Office of the President in the Carter administration. He is a longtime director of Amgen Inc. He chairs the Human Proteome Project of the international Human Proteome Organization (HUPO). He is a Member of the Institute of Medicine of the National Academies (IOM), the Association of American Physicians, and the American College of Physicians. He was President and Board Chair of the American Association for the Advancement of Science, chaired the presidential/congressional Commission on Risk Assessment and Risk Management ("Omenn Commission"), served on the National Commission on the Environment, and chaired the NAS/NRC/IOM Committee on Science, Engineering and Public Policy. He is a Member of the Scientific Management Review Board for the National Institutes of Health. He is a Fellow of the American Academy of Arts and Sciences.

Thomas D. Pollard is Dean of the Graduate School of Arts and Sciences, Sterling Professor of Molecular, Cellular & Developmental Biology, and Professor of Cell Biology and of Molecular Biophysics and Biochemistry at Yale University. His research focuses on biochemical and biophysical analysis of the actin cytoskeleton. Prior to his appointment at Yale in 2001, he served as President of the Salk Institute, where he was also a Professor. From 1977 to 1996, he was Professor and Director of the Department of Cell Biology and Anatomy at Johns Hopkins Medical School. He was previously on the faculty of Harvard Medical School. A former President of the American Society for Cell Biology and the Biophysical Society, he is a Fellow of the National Academy of Sciences and a Member of the Institute of Medicine of the National Academies. He is the recipient of the Rosenstiel Award, E.B. Wilson Medal, and Gairdner International Award in Biomedical Sciences. He is a Fellow of the American Academy of Arts and Sciences.

Robert C. Richardson† was F. R. Newman Professor of Physics at Cornell University. He served on the Cornell faculty since 1967 and was the Director of the Laboratory of Atomic and Solid State Physics from 1990 to 1997. After 32 years of teaching undergraduates and leading an active research program in studies of matter at very low temperatures, he served as the Vice Provost for Research and as the Senior Science Advisor to the Provost and President of Cornell University. In the fall of 1971, in collaboration with David Lee and Douglas Osheroff, he made the accidental discovery that liquid undergoes a pairing transition similar to that of superconductors. For that work they were awarded the Simon Prize in 1976, the Buckley Prize in 1981, and the Nobel Prize in 1996. Richardson was awarded Guggenheim Fellowships in 1975 and in 1982 and he was a Member of the National Academy of Sciences and the American Philosophical Society. He served on several boards, including the National Science Board, the governing body of the National Science Foundation; The Duke University Board of Trustees; the Board of Directors of the American Association for the Advancement of Science; and the Board on Physics and Astronomy of the NRC. He was Cochair of the National Research Council Committee on "Understanding the Impact of Selling the U.S. Helium Reserve." He was a Fellow of the American Academy of Arts and Sciences.

David D. Sabatini is the Frederick L. Ehrman Professor of Cell Biology at NYU School of Medicine. As a molecular cell biologist, skilled in both morphological and biochemical approaches, he was a key figure in laying the foundation for the field of intracellular protein trafficking with his seminal studies on co-translational translocation of nascent polypeptides in the endoplasmic reticulum and the intracellular sorting of plasma membrane proteins in polarized epithelial cells. He is a Member of the National Academy of Sciences and of the Institute of Medicine of the National Academies, and a Foreign Associate of the French Academy of Sciences, which awarded him the Grand Medaille d'Or in 2003. President Chirac also named him a Chevalier of the French Legion of Honor in 2006. He is a Fellow of the American Academy of Arts and Sciences and serves as a member of the Academy's Council and Trust.

† *Deceased*

Randy Schekman is Professor in the Department of Molecular and Cell Biology at the University of California, Berkeley; Howard Hughes Medical Institute Investigator; and Founding Editor-in-Chief of *eLife*, an Open Access journal supported by the HHMI, the Wellcome Trust, and the Max Planck Society. He is also an Adjunct Professor of Biochemistry and Biophysics at the University of California, San Francisco. At Berkeley, he developed a genetic and biochemical approach to the study of eukaryotic membrane traffic. Among his honors are the Eli Lilly Award in Microbiology and Immunology, the Lewis S. Rosenstiel Award in Basic Biomedical Science, the Gairdner International Award, the Amgen Award of the Protein Society, the Albert Lasker Award for Basic Medical Research, and the Louisa Gross Horwitz Prize of Columbia University. He was President of the American Society for Cell Biology and Editor of the *Annual Review of Cell and Developmental Biology*. He served as Editor-in-Chief of the *Proceedings of the National Academy of Sciences* from 2006 to 2011. He is a Member of the National Academy of Sciences and the American Philosophical Society and a Fellow of the American Academy of Arts and Sciences.

Richard H. Scheller is Executive Vice President of Genentech Research and Early Development (gRED). He is responsible for overseeing the strategy for Genentech's research, drug discovery, business development, and early development activities (through proof of concept in the clinic). He serves on Genentech's Research Review Committee and is a member of Genentech's Executive Committee and the Enlarged Roche Corporate Executive Committee. He joined Genentech in 2001 as Senior Vice President of Research. In 2003, he was promoted to Executive Vice President of Research and was appointed Chief Scientific Officer in 2008. He assumed his current role as Executive Vice President and Head of Genentech Research and Early Development following the Roche merger in 2009. He obtained his first academic appointment to Stanford University in 1982, and was appointed Professor of Molecular and Cellular Physiology and Biological Sciences in 1993. He was appointed Investigator, Howard Hughes Medical Institute, Stanford University Medical Center in 1994 (through 2001). He has been an Adjunct Professor in the Department of Biochemistry and Biophysics at the School of Medicine, University of California, San Francisco, since 2004. His work has earned him numerous awards, including the 2010 Kavli Prize in Neuroscience and the 1997 U.S. National Academy of Sciences Award in Molecular Biology. He is a Member of the U.S. National Academy of Sciences, and has served on numerous advisory boards, including the U.S. National Advisory Mental Health Council of the U.S. National Institutes of Health. He is a Fellow of the American Academy of Arts and Sciences.

Henri A. Termeer served as Chairman, President, and Chief Executive Officer of Genzyme Corporation for nearly three decades. He retired from Genzyme in June 2011. In 2008, he was appointed to Massachusetts Governor Deval Patrick's Council of Economic Advisors and is Cochair of the Leadership Council of the Massachusetts Life Sciences Collaborative.

He is Chairman Emeritus of the New England Healthcare Institute. He is a Board Member of Abiomed, Inc., AVEO Pharmaceuticals, Verastem, Inc., and Medical Simulation. In addition, he is a Board Member of the Massachusetts Institute of Technology Corporation and serves on its Executive Committee, a Director of Massachusetts General Hospital, a Board Member of Partners HealthCare, and a Member of the Board of Fellows of Harvard Medical School. He was Chairman of the Board of Directors of the Federal Reserve Bank of Boston from 2010 to 2011 and served on the Board of Directors of the Pharmaceutical Research and Manufacturers of America. He is a Fellow of the American Academy of Arts and Sciences.

Samuel Thier is Professor Emeritus of Medicine and Professor Emeritus of Health Care Policy at Harvard Medical School. From 1996 to 2002, he served as President and Chief Executive Officer of Partners HealthCare System and, from 1994 to 1997, he was President of Massachusetts General Hospital. Prior to that, he served as President of Brandeis University. He served for six years as President of the Institute of Medicine of the National Academies and eleven years as Chairman of the Department of Internal Medicine at Yale University School of Medicine. He is a Trustee Emeritus of Cornell University and a Director of Charles River Laboratories, Inc. He previously served as Chairman of the Commonwealth Fund and the Federal Reserve Bank of Boston. He is a Fellow of the American Academy of Arts and Sciences.

The scientific and technological opportunities of the twenty-first century are enormous. At the same time, there are pressing societal issues in health, energy, the environment, food, and water. The American Academy's *ARISE II* report highlights the path to realize the full potential of the American research enterprise and address these societal issues by calling for deep integration across the physical and life sciences, as well as deep integration between the basic discovery and applied research aspects of science. The report makes specific, thoughtful recommendations for how to facilitate cooperative, synergistic interactions between academia, industry, and government that are critical for success.

—**Peter S. Kim,** President, Merck Research Laboratories

Scientists must purposefully address the global challenges that face science and society. *ARISE II* points to a culture of collaboration to advance the human condition and protect our planet.

—**Bassam Z. Shakhashiri**, William T. Evjue Distinguished Chair for the Wisconsin Idea and Professor of Chemistry, University of Wisconsin-Madison ; former President, American Chemical Society

Not surprisingly, given the extraordinary accomplishments of the report's authors, within its pages are to be found numerous important recommendations to strengthen America's position in research and innovation. The message appropriately focuses on breaking barriers—such as those that exist among government, industry, and academia and those that continue to persist even among scientific disciplines. Meeting this challenge is particularly important given the problems facing the nation today. But the case is also compellingly made that there is a critical role for research that is purely curiosity-driven.

—**Norman Augustine**, Retired Chairman and Chief Executive Officer, Lockheed Martin Corporation

The past few decades have witnessed an explosion of new and highly specialized scientific and technical insights across various fields. This increasing scientific complexity has often coincided with decreasing R&D productivity as people struggle to understand, synthesize, and leverage specific advances in the process of invention. Undoubtedly, this illustrates the value of integration and collaboration across scientific disciplines. The *ARISE II* report provides a useful road map for academia, policy-makers, and industrial leaders who seek to increase America's ability to translate cutting-edge scientific and technical approaches into practical innovation that meets the needs of society.

—**Kenneth Frazier**, Chairman of the Board, President, and Chief Executive Officer, Merck & Company, Inc.

By focusing so clearly on the necessity for transdisciplinary research and seamless collaboration between academia, government, and the private sector, the members of the *ARISE II* report have highlighted two aspects of the current scientific and technological enterprise that need reform if the United States is to retain its preeminence in innovation that fosters future economic prosperity. Their recommendations are realistic actions that all stakeholders in America's future should take under serious consideration.

—**Shirley M. Tilghman**, President, Princeton University

ARISE II takes on the daunting challenges of tearing down the academic silos, fostering transdisciplinary research and education, and discussing ways to bridge the academic-industrial chasm. This is a timely and critical focal point. The report gives excellent historical context and sage advice for moving forward. I consider it inspiring!

—**Thomas Cech**, Distinguished Professor, University of Colorado Boulder; former President, Howard Hughes Medical Institute

Science has the power to change our lives for the better. It is hamstrung today by boundaries: boundaries between disciplines and among academia, industry, and government. These are cemented in place by outmoded funding and departmental and educational structures. *ARISE II* analyzes these issues and suggests steps to establish novel boundary-free zones for transdisciplinary science. The analysis is clear and the suggestions eminently implementable. The first institutions and governments to do so will open floodgates for new discoveries, new businesses, and new life-improving innovations.

—**Mark C. Fishman**, President, Novartis Institutes for BioMedical Research